Current Status of $PM_{2.5}$ Pollution and its Mitigation in Vietnam

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Abstract

Vietnam is experiencing serious fine particulate matter ($PM_{2.5}$) pollution as a result of local activities and long-range transport (LRT) pollutants. In this article, we summarize and analyze $PM_{2.5}$ data from ground stations and manual measurements showing $PM_{2.5}$ status, characteristics and emission sources in the period from 1996 to 2017 in Vietnam. In addition, we provide a brief impact assessment of $PM_{2.5}$ pollution on public health regarding diseases and deaths. Conscious of $PM_{2.5}$'s harmful effects, Vietnam has been taking steps to mitigate $PM_{2.5}$ pollution in various forms through efforts by the government, non-governmental organizations, media, communities and individuals, and has obtained initial results. This article presents a comprehensive review of current $PM_{2.5}$ pollution and its mitigation in Vietnam.

Key words : current status, mitigation, $PM_{2.5}$ pollution, Vietnam

1. Introduction

In Vietnam, air pollution has been increasing rapidly as a result of local pollution from traffic, construction, industries, agriculture, domestic cooking, heating, etc., with no effective treatment, compounded by long-range transport (LRT) pollutants. At present, many major cities face high levels of air pollution, especially fine particulate matter concentrations (i.e., $PM_{2.5}$). Monitoring data in recent years have shown that $PM_{2.5}$ levels in urban areas are generally high and exceed national standards many days in a year, especially in urban areas in the north (MONRE, 2016).

$PM_{2.5}$ refers to atmospheric particulate matter with a diameter of less than 2.5 μm, usually having acidic characteristics with a longer lifetime in the atmosphere and deeper penetration into the lungs than larger dust particles. Global Burden of Disease (GBD) estimated that exposure to ambient $PM_{2.5}$ accounted for 806,900 disability-adjusted life-years (DALYs) in Vietnam in 2015 (Cohen *et al.*, 2017). Exposure to $PM_{2.5}$ can cause respiratory and cardiovascular diseases, cancer, bronchial pneumonia, strokes and even death if exposure is prolonged.

Conscious of $PM_{2.5}$'s harmful effects on the environment and public health, Vietnam has been taking concrete steps to mitigate $PM_{2.5}$ pollution. The Vietnamese government has focused on designing an environmental regulatory system; developing comprehensive environmental laws and standards; approving and implementing programs to control, reduce and remedy environmental pollution; maintaining and enlarging air pollution monitoring networks; and enhancing public awareness. Furthermore, many non-governmental organizations and communities have been getting involved in environmental protection activities.

In this article, we present a comprehensive picture of $PM_{2.5}$ pollution in Vietnam based on a synthesis and analysis of related works about $PM_{2.5}$ measurements, characteristics and emission sources. We then investigate studies to assess the impact of $PM_{2.5}$ on public health in Vietnam. $PM_{2.5}$ mitigation policies and solutions by the Vietnamese government, organizations and communities are then summarized and discussed.

2. Study Area

Vietnam, located in the middle of Southeast Asia, covers an area of 331,698 km^2 extending from (8° 27' N, 102° 8' E) to (23° 23' N, 109° 27' E) with an estimated 94.6 million inhabitants as of 2016. Vietnam is bordered by China to the north, Laos and Cambodia to the west, and the East Sea and Pacific Ocean to the east and southeast. With a tropical monsoon climate and frequently changing weather, Vietnam is divided into seven climatic zones: northwest (NW), northeast (NE), Red River Delta (RRD), north central (NC), south central (SC), central highland (CH), and southeast (SE). The north, including the NW, NE, RRD and NC, has two major seasons: winter, from October to March, which is cold and dry with monsoon winds blowing from the northeast along the Chinese coast and across the Gulf of Tonkin; and summer, from May to August, which is dominated by hot, dry southwest winds and wet southeast winds. In the south, consisting of SC, CH and SE, there is a northeast wind in the dry season and southwest wind in the rainy season (Fig. 1). The average relative humidity is 84% throughout the year. The annual rainfall ranges from 1,200 to 3,000 mm and sunny hours from about 1,500 to 3,000 hours per year. In the north, the temperature varies from 5℃ in December to 37℃ in July or August. The seasonal variation is less in the south, with temperatures ranging from 21 to 28℃. Geographical and climatic factors strongly affect $PM_{2.5}$ pollution in each region of Vietnam.

The environment in Vietnam is strongly influenced by socio-economic development activities. According to statistics from the General Statistics Office, Vietnam's population is now more than 94.6 million (2016) with an annual growth rate of 1 million. The population density in the Red River Delta, Mekong Delta and southeast (59.5% of the population) is higher than in the north central, south central, northwest, northeast and central highland (19%). As of December 2015, Vietnam had 787 urban areas with about 31 million people. The urbanization rate has increased by an average of 1.0 to 1.02% per year, which is equivalent to 1 to 1.2 million urban inhabitants. Urbanization has accelerated in Hanoi and Ho Chi Minh City at annual rates of 3.8% and 4%, respectively. Population growth and urbanization have led to strong infrastructure development (i.e., roads, houses, etc.) and a large number of vehicles. $PM_{2.5}$ emissions are increasing as a result of people's cooking and heating, transportation, and construction activities in urban environments.

Air pollutant emissions from traffic predominate in Vietnam. As of 2015, Vietnam had a circulation of nearly 2 million cars and over 45 million motorbikes. Hanoi alone had 300,000 automobiles, including 1,300 buses and 14,000 taxicabs, and 4.6 million motorcycles in 2013. Ho Chi Minh City had 654,537 cars and 6,495,702 motorcycles and motorbikes within it, together with about 1 million motorbikes and 60,000 cars outside the city in 2015. Since motor vehicles mostly use gasoline and diesel fuel, major air pollutants are generated through their exhaust gases from the combustion of engine fuels. Furthermore, at crossroads and intersections, air pollution levels are higher than in other areas as a result of vehicle acceleration and restart. Narrow and degraded roads causing traffic congestion are significant factors in serious air pollution, especially in large cities such as Hanoi and Ho Chi Minh City.

The Vietnamese economy includes services (40.52%), industry and construction (33.09%), agriculture, forestry and fisheries (16.30%), and product taxes minus product subsidies (10.09%) as of 2015 (MONRE, 2015). As major sectors of the economy, industrial, craft, construction and agricultural activities have been increasing and therefore, putting high pressure on the environment, especially $PM_{2.5}$ pollution. Currently, Vietnam has 283 industrial zones distributed in different regions and 5,096 craft villages and other small production facilities (MONRE, 2015). $PM_{2.5}$ results mainly from industrial and craft activities involving cement, metallurgy, mining, thermal power production, and so on. In addition, livestock farming, rice or vegetable cultivation and aquaculture also put pressure on the environment. $PM_{2.5}$ from agriculture is associated with rice straw and rice stub burning for soil preparation after harvest in the northern mountainous areas, the Red River Delta and Mekong River Delta.

3. Current Status of $PM_{2.5}$ pollution

Air pollution is a serious problem in Vietnam. Air pollutants, including TSP, PM_{10}, $PM_{2.5}$, PM_1, NO_2, SO_2 and CO, exceed national standards many days in urban and high-traffic areas of cities such as Hanoi, Hai Duong, Bac Ninh, Hung Yen, Viet Tri and Ho Chi Minh City; industrial zones in Ha Giang, Hanoi, Hai Phong, Quang Ninh, Can Tho and other areas; and craft villages in places such as Hanoi, Ninh Binh, Bac Ninh and Hung Yen. Additionally, Vietnam's north suffers from LRT pollutants in winter (MONRE, 2015). In the current air pollution situation, $PM_{2.5}$ pollution is considered the most serious problem in Vietnam.

3.1 Monitoring Network

In Vietnam, $PM_{2.5}$ monitoring has been carried out by the Center for Environmental Monitoring (CEM), Vietnam Environment Administration (VEA) of Ministry of Natural Resources and Environment (MONRE) since 2010. Automatic, real-time monitoring systems were installed at road sites in Hanoi (two stations), Quang Ninh (one station), Viet Tri (one station), Hue (one station), Da Nang (one station) and Nha Trang (one station), with a distribution as shown in Fig. 1. Providing continuous PM mass measurements is the GRIMM model 180. The CEM monitoring data are available to the public at the cem. gov. vn website.

In addition, provinces such as Hanoi, Ho Chi Minh City, Quang Ninh, Vinh Phuc, Dac Lac and Dong Nai have recently been investing in their own environmental monitoring networks. One notable monitoring network is the 10-station Air Quality Monitoring System (AQMS) in Hanoi installed in 2017 (Fig. 1). The Hanoi stations monitor air pollutants, including $PM_{2.5}$, collect data and transfer it for processing at the center using XR® software. The information is directly published online for the public at http://moitruongthudo.vn. The system was designed by Airparif, France.

In response to increasing $PM_{2.5}$ in Vietnam, the US

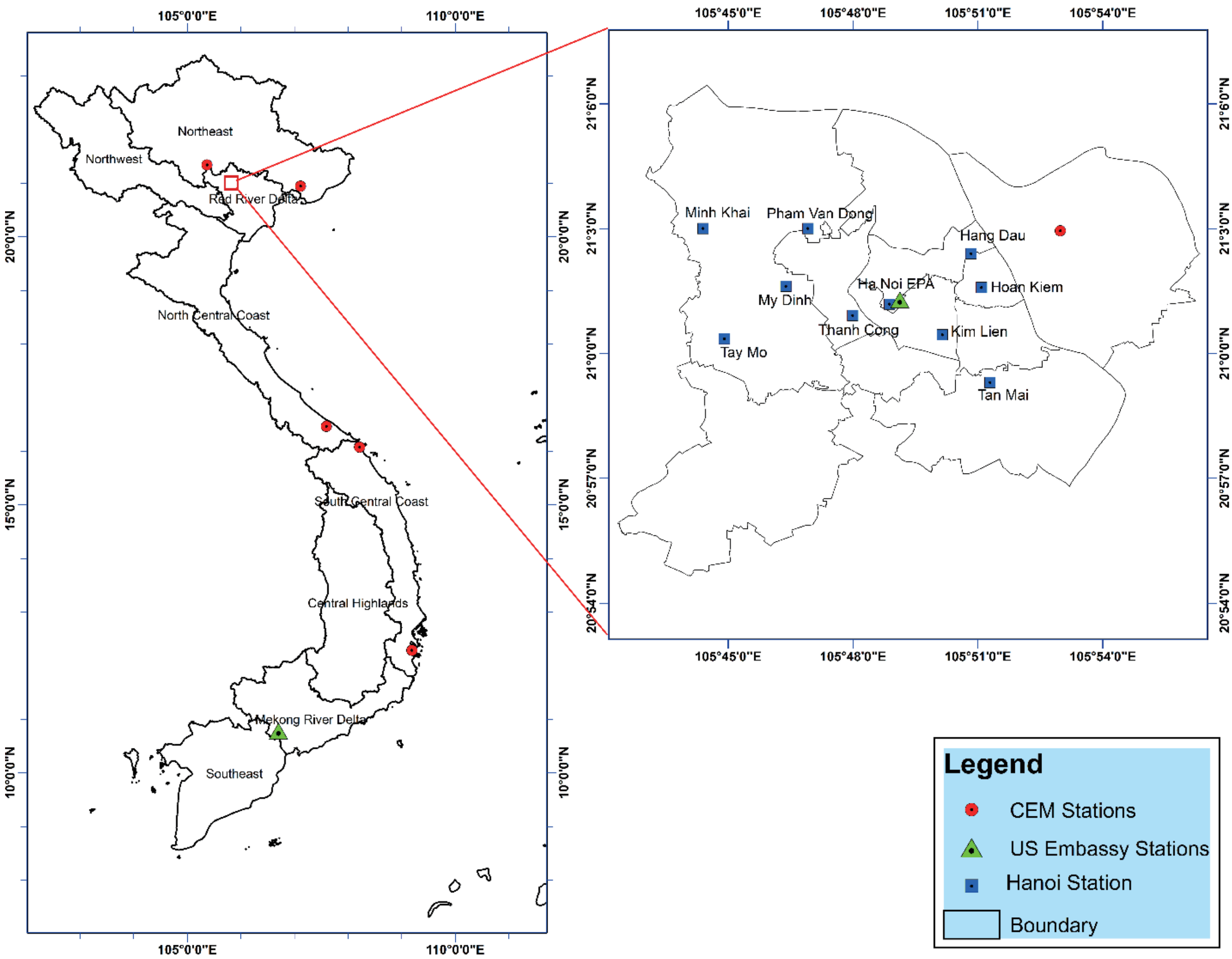

Fig. 1 Vietnamese climate zones and distribution of ground monitoring stations operated by CEM, the US Embassy and Hanoi.

Embassy has installed two automatic observation stations at 7 Lang Ha, Ba Dinh, Hanoi in April 2015 and 4 Le Duan, District 1, Ho Chi Minh City in January 2016 (Fig. 1). The equipment is Met One's BAMs. The device is located at the specified position to measure the ambient air environment. Monitoring data at these stations are available at www. airnow. gov.

Besides automatic and continuous monitoring networks, regular periodic sampling is conducted three to six times per year at more than 100 sites and six to 12 sites for national and local observation programs, respectively, but they do not measure $PM_{2.5}$. In addition, other studies aiming to measure $PM_{2.5}$, analyze its composition and identify emission sources have carried out measurements in many provinces at sites with different environments several decades ago (Table 1). Recently, satellite imagery has been used to map estimated $PM_{2.5}$ concentrations over Hanoi between August 2010 and July 2012 (Nguyen *et al.*, 2013) and Vietnam from December 2010 to September 2014 (Nguyen *et al.*, 2015). CALIPSO satellite data are beginning to be used for analysis of pollution sources in Vietnam (Tran *et al.*, 2018).

3.2 Status of $PM_{2.5}$ Pollution

3.2.1 Annual Variation of $PM_{2.5}$

Automatic and continuous monitoring stations for $PM_{2.5}$ were established at different locations and times. Annual variation of $PM_{2.5}$ in Vietnam is ascertained based on analysis of yearly averaged $PM_{2.5}$ recorded from ground stations operated by CEM and the US Embassy (USE). Annual $PM_{2.5}$ is calculated when ground stations work correctly and only if there are enough data be to representative of a year, as follows: Hanoi (January 2010 to July 2017 at the CEM station and January 2016 to December 2017 at the USE station), Viet Tri (April 2013 to December 2016), Ha Long (January 2014 to December 2017), Hue (April 2013 to December 2015), Da Nang (January 2011 to December 2016), Nha Trang (March 2012 to October 2016), and Ho Chi Minh (February 2016 to December 2017) (Fig. 2). Before 2009, yearly averaged $PM_{2.5}$ was monitored and reported by various thematic studies (Fig. 3).

Vietnamese northern provinces such as Viet Tri, Ha Long and Hanoi have annual $PM_{2.5}$ concentrations much exceeding the standards. In Hanoi, $PM_{2.5}$ increased from 1998 to 2011 (Figs. 2 and 3) and decreased from 2012

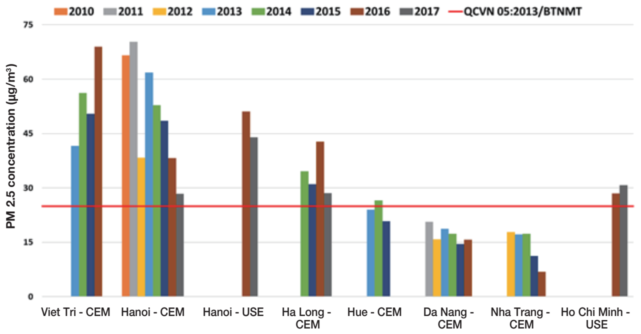

Fig. 2 Yearly averaged PM $_{2.5}$ at six CEM stations and two USE stations. The red line is the standard for annual $PM_{2.5}$ under Vietnamese technical regulations.

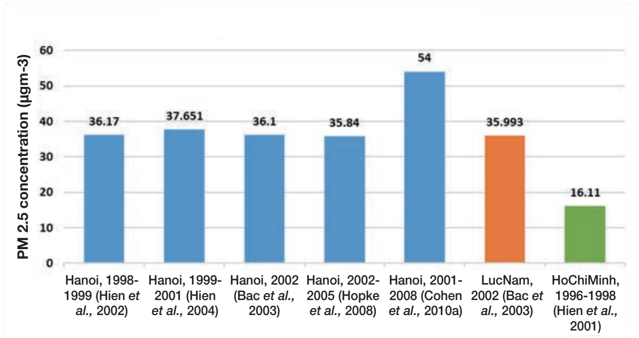

Fig. 3 Yearly averaged $PM_{2.5}$ at Hanoi, Luc Nam and Ho Chi Minh City before 2009, obtained from literature.

to 2017 (Fig. 2). In the period of 2010 to 2012, rapid economic development led to increased construction and traffic in Hanoi. Since 2012, economic activities have decreased compared to previous times. Moreover, local authorities have implemented projects and programs to control and reduce air pollution. This can explain the trends in air pollution in Hanoi. Hanoi, however, still suffers the highest $PM_{2.5}$ pollution in Vietnam, followed by Viet Tri and Ha Long. Hue City, located in central Vietnam, has annual $PM_{2.5}$ concentrations approximately equal to the national standard. Moving into the southern provinces where the weather varies less and is not under the influence of the northeast monsoon, in Da Nang and Nha Trang, $PM_{2.5}$ is under the permitted limit. However, in Ho Chi Minh City, one of the largest cities in southern Vietnam, $PM_{2.5}$ has been increasing in comparison to 1996 levels (Fig. 3) and has neared the national limit in recent years (Fig. 2) as a result of urbanization.

3.2.2 Seasonal Variation of $PM_{2.5}$

The northern provinces of Vietnam including Viet Tri, Ha Long (northeast), and Hanoi (Red River Delta) are strongly influenced by the north and northeast monsoons, which bring dust pollution from far away (i.e., LRT) during the winter months. In addition, the dry climate and high pressure during this time cause $PM_{2.5}$ to accumulate and limit its dispersion by air. In contrast, the northern provinces are affected by southwesterly and southeasterly winds blowing out to sea or to the north and frequent rains washing out air pollution in the summer. As a result, the northern provinces have higher $PM_{2.5}$ concentrations in winter than in summer. Figure 4 shows monthly $PM_{2.5}$ concentrations at the ground stations operated by CEM and USE. The monitoring stations in Hanoi, Viet Tri and Ha Long show seasonal variations in which $PM_{2.5}$ is particularly high in the months of October to March, lower in the transition months of April and September, and lowest in the summer months from May to August. Hue City is still affected by seasonal trends. The monthly averaged PM2.5 is still the highest in Hanoi, about twice the levels in the other northern provinces, even in the rainy season. It is followed by the provinces of Viet Tri, Ha Long and Hue (Fig. 4a).

The southern provinces have a mild climate with less variation. In the dry season, the northeast monsoon and southeasterly wind dominate. During the rainy season, southwesterly winds bring about 90% of the total annual rainfall (southwest monsoon). In addition, Vietnam's south is located near the equator and separated from the north by the Hai Van Pass, the region is less affected by the northeast monsoon and has just two seasons in a year. Therefore, $PM_{2.5}$ does not change significantly in the southern provinces (i.e., Da Nang, Nha Trang and Ho Chi Minh) with the season. The monthly $PM_{2.5}$ in Ho Chi Minh City, however, was higher than in Da Nang and Nha Trang, a result of its rapid urbanization (Fig. 4b).

Previous studies have shown seasonal variation in the Vietnam's north to be exactly the same trend as seen in the station data analysis above. This seasonal variation was reported for Hanoi in Hien *et al.* (2002), Dung Hai and Kim-Oanh (2013) and Snider *et al.* (2016); for Tam Dao, a mountainous province in the north of Vietnam, in Co *et al.* (2014); and for Quang Ninh, a coal mining and tourism city, in Hang and Kim-Oanh (2010) (see Table 1 for detailed information). Maps of estimated $PM_{2.5}$ from satellite images in 2010 to 2014 over Vietnam present the seasonal variations (Nguyen *et al.*, 2015).

3.2.3 Diurnal Variation of $PM_{2.5}$

Figure 5 presents the diurnal variations of $PM_{2.5}$ in the rainy and dry seasons at each ground station following seasonal separation rules in Hien *et al.* (2002) and Vinh *et al.* (2018). CEM monitoring stations were located in areas with traffic where the daily $PM_{2.5}$ pattern often reflects fluctuations in hourly vehicular traffic. The $PM_{2.5}$ concentration increased during rush hours in the morning (7:00-8:00 am) and afternoon (6:00-7:00 pm) but was low at noon (1:00-2:00 pm), as can be observed at the Ha Long, Da Nang, Hue and Nha Trang stations in both rainy (Fig. 5a) and dry seasons (Fig. 5b). During the dry season in the north, nocturnal radiation inversions (NRIs) and subsidence temperature inversions (STIs) occur from October to December and

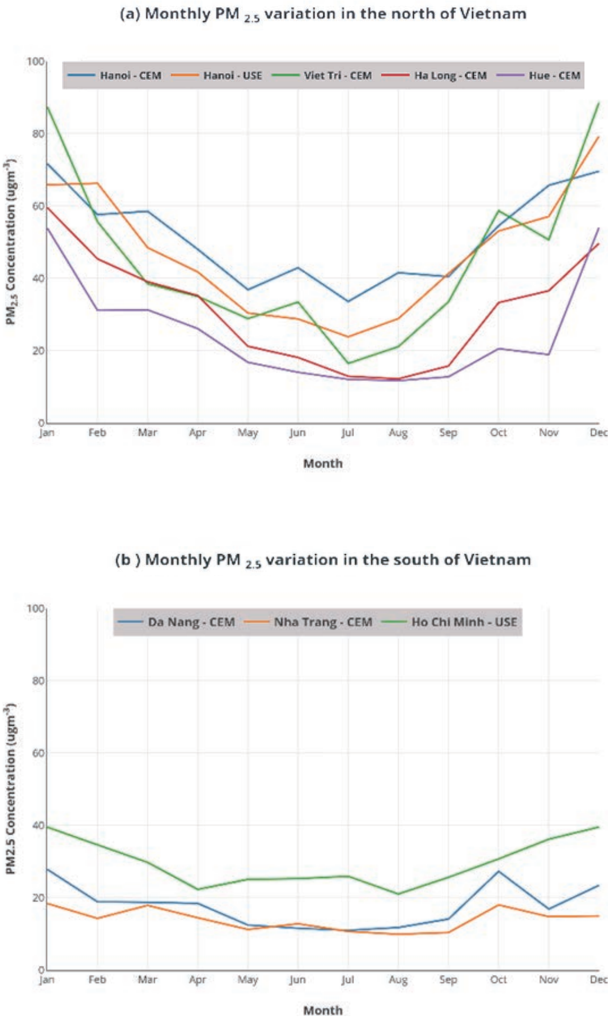

Fig. 4 Monthly average $PM_{2.5}$ at ground stations shows seasonal variations in Viet Tri, Hanoi, Ha Long and Hue (a) and no seasonal trends in Da Nang, Nha Trang and Ho Chi Minh City (b) in Vietnam.

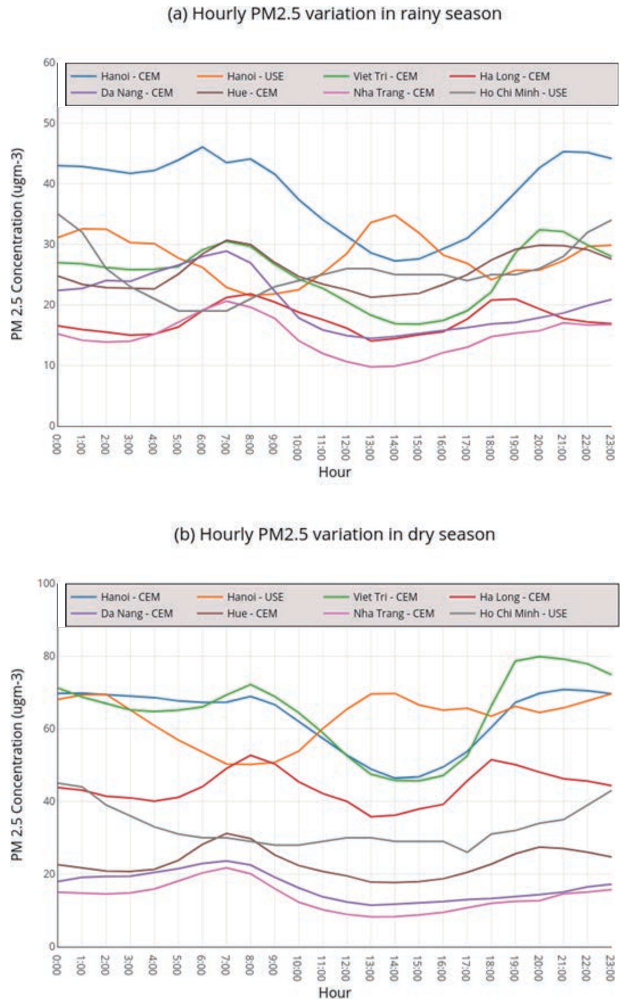

Fig. 5 Daily patterns of $PM_{2.5}$ concentrations at the CEM and USE stations in the rainy season (a) and the dry season (b).

January to March, respectively. During NRIs, the $PM_{2.5}$ concentration was much enhanced and significantly higher at night than in the day. During STI occurrences, $PM_{2.5}$ was still higher than on normal days but lower than during NRIs because it was much suppressed under humid conditions (Hien *et al.*, 2002). This explains the higher $PM_{2.5}$ observed during the night than during the day at the Viet Tri and Hanoi-CEM stations in the dry season. This diurnal variation, however, was not observed at the Hanoi-USE station (Fig. 5b). Moreover, the Viet Tri and Hanoi-CEM stations still had same night-day variation trends during the rainy season. Further investigation needs to be conducted on this. The impact of traffic on the Viet Tri and Hanoi-CEM station measurements is more apparent in the rainy season when the climate has less of an influence (Fig. 5a).

In contrast, the USE observation stations were located in residential areas, thus their $PM_{2.5}$ concentrations showed no traffic impact. At the USE Hanoi station, the $PM_{2.5}$ concentration decreased in the morning, rising in the afternoon and night while no clear trends in daily variability were found at the Ho Chi Minh station (Fig. 5).

3.3 Emission Sources

Studies related to $PM_{2.5}$ emission source contribution have been conducted in past years in Hanoi, Ho Chi Minh City and some northern provinces such as Bac Ninh, Hai Duong, Luc Nam, Tam Dao and Quang Ninh. These studies measured $PM_{2.5}$ samples during a certain period, and analyzed $PM_{2.5}$ chemical compositions to determine emission sources or/and associations with air quality models to assess LRT pollution, especially for the northern provinces of Vietnam.

In Hanoi, local emission sources vary among the measurement sites and sampling periods but mainly due to traffic, industry, construction/soil, biomass burning and coal combustion (Cohen *et al.*, 2010a; Dung Hai & Kim-Oanh, 2013; Kim-Oanh *et al.*, 2006; Hopke *et al.*, 2008) (Table 1). Because of the special geographic location and climate conditions, $PM_{2.5}$ concentrations in Hanoi are often high during the dry, cold winter and strongly affected by LRT pollution arriving with the

Table 1 Summary of studies on $PM_{2.5}$ measurement and component analysis to determine emission sources in urban areas.

City	(Lat, Long); Site; Elevation; Equipment; Analytical Methods	Sampling Period	# Obs	$PM_{2.5}$ (μg/m^3)	Emission Sources	Refs.
Hanoi	(21.02° N, 105.85° E); urban site; 1.6 m, GENT SFU; IC, reflectance method and PMFA	Jan 1999 – Dec 2001	330	37.6		Hien *et al.*, 2004
		Northern trajectory (Sep/Oct to Dec)	64	49.4	LRT: 25, LB (local burning) primary emission: 14.9, soil dust: 0.3, LSA: 0.7, marine aerosols: 0.7, Cl-depleted marine aerosols: 2.6, vehicle/road dust: 2.9 (unit: μg/m^3)	
		Northeast trajectory (Jan to Mar/Apr)	68	44.2	LRT: 15.1, LB (local burning) primary emission: 6.4, soil dust: 3.6, LSA: 5, marine aerosols: 0.4, Cl-depleted marine aerosols: 1.5 (unit: μg/m^3)	
		Southwest trajectory (May to Aug)	70	20.3	LRT: 7.5, LB (local burning) primary emission: 7.5, soil dust: 0, LSA: 1.3, marine aerosols: 1.5, vehicular/road dust: 0.5, coarse nitrate: 1.1 (unit: μg/m^3)	
Hanoi	(21.02° N, 105.85° E); urban site; N/A; GENT-SFU/ACE-ASP-VN65; INAA, XRF, PIXE, IC, light eflection, PCFA, PMFA, and back trajectory.	Sep 1998 – Aug 1999	333	40.7		Bac *et al.*, 2003
		Sep 1999 – Aug 2000		35.7		
		Sep 2000 – Aug 2001		34.5		
		Sep 2001 – Aug 2002		36.1		
		2002			$(NH_4)_2SO_4$: 26%, organics: 31%, soil: 9%, BC: 9%, salt: 1%, unknown: 24%	
Hanoi	N/A; urban mixed site/residential site/ commercial sites; N/A; Dichot/MiniVol samplers; SRM.	2001 – 2004, dry season	75	124	Traffic, secondary sulfate and nitrate particles, biomass burning, and soil dust.	Kim-Oanh *et al.*, 2006
		2001 – 2004, wet season	21	33		
Hanoi	(21.02° N, 105.85° E); Urban site; N/A; GENT-SFU; PIXE, XRF and INAA	2002 – 2005	160	35.8 ± 15.5	Burning biofuel for cooking and home heating, two-stroke engines of motorbike	Hopke *et al.*, 2008
Hanoi	(20.938° N, 105.784° E); industrial site; 15 m; MiniVol Sampler; IC, ICP-OES and TOT	Dec 23, 2006 – Jan 7, 2007	15	76 ± 32	—	Dung Hai & Kim-Oanh, 2013
		Jan 12 – Feb 20, 2007	85	78 ± 33 (4h)	Secondary mixed (local): 40%, industry/incineration: 6%, aged sea salt mixed: 11%, secondary sulfate rich: 16%, construction/soil: 1%, residential/commercial: 16%, traffic (diesel): 10%	
Hanoi	(21.021° N, 105.807° E); urban site; N/A; teflon filter; PIXE, PIGE, RBS, PESA and He/NeLA	Apr 25, 2001 – Dec 31, 2008	748	54 ± 33	Automobiles, transport: (40 + 10)%; soil: (3.4 ± 2)%; secondary sulfates: (7.8 ± 10)%; smoke: (13 ± 6)%; industry: (19 ± 8)%; coal: (17 ± 7)%	(Cohen *et al.*, 2010a)
Hanoi	(21.021° N, 105.807° E); urban site; N/A; teflon filter; PIXE, PIGE, RBS, PESA, He/NeLA and PMFA	Soil extreme events from Apr 2001 – Dec 2008	28	—	Taklamakan and Gobi deserts contribute 76% of soil extreme events in Hanoi	(Cohen *et al.*, 2010b)
		Coal extreme events from Apr 2001 – Dec 2008	25	—	Coal fired power stations and their contributions to coal extreme events in Hanoi: Guangxi (22%), Hunan (13%), Hubei (8.4%), Anhui (6.4%), Jangxi (5.5%) Jiangsi (4.4%) in China and Pha Lai, Na Duong, Uong Bi (15%) in Vietnam	
Hanoi	(21.048° N, 105.800° E); Urban; 10 m; PTFE filters; IC, ICP-MS, SSR, SPHM, and MB	May – Aug 2015	—	39.4 ± 3.9	Conducted composition analysis but no conclusion on emission source contribution	(Snider *et al.*, 2016)
Bac Ninh, Hai Duong	(21° 1′N, 105° 51′E); 6 rural sites; N/A; teflon filter; EDXRF and BSR	May – Oct 2000	—	—	Coal (mainly emitted from Pha Lai thermal power plant) and fuel oil combustion were major sources; biomass burning and road transport were remarkable. River transport and LRT pollution were observed.	(Gatari *et al.*, 2006)
Luc Nam	(21.18° N, 106.33° E); rural site; N/A; GENT-SPU and ACE-ASP-VN65; INAA, XRF, PIXE, IC, light reflection, PCFA, PMFA, and back trajectory	2001	224	35.993	Conducted composition analysis but no conclusion on emission source contribution	(Bac *et al.*, 2003)
Tam Dao	(21.457° N, 105.644° E); N/A; Dichot and MiniVol Samplers; IC, XRF, ICP-OES, SSR, HYSPLIT	Sep – Oct 2005	30	51 ± 29	Soil/road dust and construction activities, diesel powered vehicles, biomass burning, long range transport	(Co *et al.*, 2014)
		Dec 2005 – Jan 2006	15	25 ± 12		
		Apr 2010	12	33 ± 21		
Quang Ninh	(21° 3.7′N, 107° 20.2′E); Mining site; N/A; MiniVol sampler; IC, ICP-OES, SSR, and IMPROVE_A	Dry season (Dec 2009 – Jan 2010)	33	60 ± 23	Diesel road: 13%; biomass burning: 20%; secondary inorganic: 41.6%; diesel ship: 22%; miscellaneous: 3.8%. Percent explained: 85%	(Hang & Kim-Oanh, 2014)
		Wet season (Jul – Aug 2009)	21	35 ± 16	Diesel road: 17%; biomass burning: 41%; secondary inorganic: 16.4%; diesel ship: 24%; miscellaneous: 1.4%. Percent explained: 67%	
	(21° 5.831′N, 107° 21.773′E); Rural site; N/A; MiniVol sampler; IC, ICP-OES, SSR, and IMPROVE_A	Dry season (Dec 2009 – Jan 2010)	25	53 ± 17	Diesel road: 14%; biomass burning: 22%; secondary inorganic: 38.8%; diesel ship: 15%; miscellaneous: 11%. Percent explained: 97%	
		Wet season (Jul – Aug 2009)	22	27 ± 12	Diesel road: 26%; biomass burning: 1.7%; secondary inorganic: 41.9%; diesel ship: 29%; miscellaneous: 1.4%. Percent explained: 77%	
Ho Chi Minh City	(10° 47′N, 106° 40′E); 10 m; GENT SFU; INAA, PCFA, and polarography method	Aug 1996 – May 1998	122	16.1	Soil dust: (14 ± 3)%; biomass burning: (8 ± 2)%; secondary particles: (25 ± 1)%; road dust: (13 ± 2)%; vehicles: (17 ± 2)%; coal: (10 ± 2)%; industry: (13 ± 2)%;	(Hien *et al.*, 2001)

"N/A" indicates no information; "SFU," stack filter unit; "IC," ion chromatography; "PMFA," positive matrix factorization analysis; "INAA," instrumental neutron activation analysis; "XRF," X-ray fluorescence; "PIXE," particle-induced X-Ray emission; "PCFA," principal component factor analysis; "SRM," standard reference material; "ICP-OES," inductively coupled plasma-optical emission spectroscopy "TOT," thermal-optical transmittance method; "FIGE," particle-induced gamma-ray emission; "RBS," Rutherford backscattering; "PESA," proton elastic scattering analysis; "He/NeLA," standard He/Ne laser absorption techniques; "ICP-MS," inductively coupled plasma mass spectrometry; "SSR," smoke stain reflectometer; "SPHM," single-parameter hygroscopicity by mass; "MB," mass balance; "EDXRF," energy dispersive X-ray fluorescence; "BSR," black smoke reflectometer; and "IMPROVE_A," DRI Model 2001 Thermal/Optical Carbon Analysis (TOR/TOT) of Aerosol Filter Samples.

north and northeast monsoons. LRT pollution was reported to contribute 50%, 34% and 33% to $PM_{2.5}$ in Hanoi with northerly winds from October to December, the northeast monsoon over the East China Sea from January to March, and the southwest monsoon blowing through the Indochina Peninsula from May to July, respectively (Hien *et al.*, 2004). In another study, soil from the Chinese Taklamakan and Gobi deserts contributed 76% of the extreme events for soil. Meanwhile, four thermal power plants in China contributed 50% and three thermal power plants in Vietnam contributed 15% during days of extreme coal events in Hanoi with north and northeast monsoons (Cohen *et al.*, 2010b). Aside from Hanoi, emission sources were also reported for rural areas of Bac Ninh and Hai Duong (Gatari *et al.*, 2006), a coal mining area and a rural area in Quang Ninh (Hang & Kim-Oanh, 2010), a rural mountainous area in Tam Dao (Co *et al.*, 2014), and an urban area in Ho Chi Minh City (Hien *et al.*, 2001) (Table 1).

In addition, the emission inventory approach and satellite observation give other views of emission sources. A recent study took measurements for estimating $PM_{2.5}$ emission factors for traffic in Ho Chi Minh City (Huong Giang & Kim-Oanh, 2014). Hong Van *et al.* (2014) and Lasko *et al.* (2017) calculated a $PM_{2.5}$ emission inventory from rice straw/stubble burning. Tran *et al.* (2017) determined emission sources in three regions: Hanoi, Nha Trang and Bac Lieu, using satellite images from CALIPSO.

3.4 Impact of $PM_{2.5}$ Pollution on Public Health in Vietnam

Exposure to ambient particular matter (PM) might increase hospitalization and mortality, thus contributing to an increase in the burden of diseases in Vietnam. GBD estimated that exposure to ambient $PM_{2.5}$ accounted for 806,900 DALYs (95% uncertainty interval (UI) from 614,900 to 1.0143 million) in Vietnam in 2015 (Cohen *et al.,* 2017). Exposure to PM is leading to increased mortality in Vietnam. Deaths attributable to PM were 42.2 thousand (95% UI: 32,000−52,300) in 2015 (Cohen *et al.,* 2017). These numbers have increased in recent years. Figure 6 presents deaths attributable (in thousands) to exposure to ambient PM in Vietnam from 1990 to 2015.

Mortality from respiratory diseases (including lower respiratory infections in children under five years of age, tracheal, bronchial and lung cancer and chronic obstructive pulmonary disease) accounted for most premature deaths attributable to ambient $PM_{2.5}$ in Vietnam. Particularly, $PM_{2.5}$ accounted for 21.7%, 21.5% and 15.2% of deaths due to chronic obstructive pulmonary disease, lower respiratory infections in children under five and tracheal, bronchial and lung cancer, respectively, in 2015. In addition, ambient $PM_{2.5}$ also contributed significantly to deaths due to ischemic heart disease in Vietnam, estimated at about 15.3% of ischemic heart disease cases.

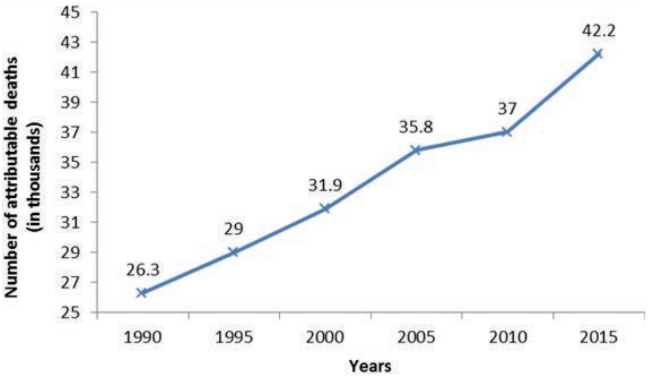

Fig. 6 Deaths attributable to exposure to $PM_{2.5}$ in Vietnam 1990-2015 (data from Cohen *et al.,* 2017).

On the other hand, Koplitz *et al.* (2017) estimated that $PM_{2.5}$ from coal-fired power plant emissions contributed to 3,357 premature deaths in 2011. Among these, deaths due to stroke contributed 1,625 to total deaths. The results of this study also indicate that the number of deaths due to exposure to pollutants from coal-plant emissions in Vietnam is far higher than in China and other neighboring countries.

$PM_{2.5}$ has been monitored in Vietnam since 2009, so the numbers of studies on short-term effects of $PM_{2.5}$ in Vietnam are sparse. To date, there have been two studies which reported short-term effects of $PM_{2.5}$ on hospitalization of children in Hanoi (Luong *et al.*, 2016; Nhung *et al.*, 2018). Nhung *et al.* (2018) pointed out that $PM_{2.5}$ was associated with hospital admissions due to pneumonia in Hanoi children under 18 years of age. Particularly, increments of an interquartile range (39.4 $\mu g/m^3$) in the seven-day-average of $PM_{2.5}$ were associated with a 5.3% (95% CI, 1.9−8.8%) increase in pneumonia hospitalization. This study, however, found no significant association between $PM_{2.5}$ and hospitalization of children for bronchitis or asthma in Hanoi. The study also confirmed that the effects are stronger in older children compared with infants. In another study, Luong *et al.* (2016) using a case-crossover approach also indicated an association between $PM_{2.5}$ and hospital admissions for respiratory disease, with the daily hospital admission count increasing by 2.2% per 10 $\mu g/m^3$ increase of $PM_{2.5}$ in a same day exposure.

4. Fine Particulate Matter Concentration Mitigation in Vietnam

4.1 Designing an Environmental Regulatory System

In Vietnam, MONRE is responsible for environmental management. MONRE develops strategies and legal documents on environmental protection and submits them to the government. MONRE coordinates with concerned ministries to implement schemes and programs for recovering environmental pollution, improving the environment and promulgating waste standards. Other relevant ministries including the Ministry of Home Affairs, Ministry of Industry and Trade, Ministry of Transportation, Ministry of

Construction, Ministry of Science and Technology, Ministry of Education and Training, Ministry of Finance, Ministry of Planning and Investment, Ministry of Agriculture and Rural Development and Ministry of Health need to perform the task of managing and controlling air pollution for their respective sectors. At the provincial level, the Department of Natural Resources and Environment (DONRE) in each province coordinates with other departments to develop and implement programs, plans and tasks on air pollution control and management in the provinces and cities.

4.2 Developing Comprehensive Environmental Laws and Standards for Air Quality Management

The Vietnamese legal system has always had provisions on air pollution protection and control. In 2014, Vietnam issued and began enforcing the Environment Protection Law (EPL). Under this law, obligations, tasks and activities of government, organizations, companies, individuals and others for environmental protection are determined. Regarding the atmospheric environment, the government is responsible for monitoring and assessing the quality of the ambient air environment and publishing information. In cases of air pollution, warnings must be issued and the problem handled in time (EPL, Article 63). Air pollution control focuses on direct management of emission sources. Consideration and approval of projects and activities must be based on air pollution emissions. Production, business and service establishments with large sources of industrial exhaust gas emissions need to register their pollutant sources and set up automatic, continuous monitoring equipment to measure, control and report their gas emissions (EPL, Article 64&62).

Besides the EPL, national technical regulations (abbreviated as "QCVN" following the Vietnamese term) relating to the air environment have been developed, issued, continuously reviewed and adjusted to fit the actual situation. An updated national technical regulation on ambient air quality was released in 2013 (QCVN 05: 2013/BTNMT). It specifies limit values for $PM_{2.5}$ as 50 μg/m^3 and 25 μg/m^3 for the 24-hour average and yearly average, respectively. Analytical methods to determine the $PM_{2.5}$ concentration comply with the guidelines of the following standards: (i) air quality - weighing method for determination of dust content (TCVN 5067: 1995); (ii) ambient air - measurement of the mass of particulate matter on a filter medium - beta-ray absorption method (TCVN 9469: 2012); and (iii) methods for sampling and analysis of ambient air - determination of suspended particulate matter - dichotomous sampler (PM_{10}, coarse PM and $PM_{2.5}$) - gravimetric method (AS/NZS 3580.9.7: 2009). In addition, Vietnam has also developed and issued emission standards for a number of specific sectors. National technical regulations were issued for industrial inorganic substance and dust emissions in general (QCVN 19: 2009/BTNMT) and in particular for cement (QCVN 23: 2009/BTNMT), thermal power (QCVN 22: 2009/BTNMT), chemical fertilizers (QCVN 21: 2009/BTNMT), industrial waste incinerators (QCVN 30: 2012/BTNMT), medical solid waste incinerators (QCVN 02: 2012/BTNMT) and domestic solid waste incinerators (QCVN 61-MT: 2016/BTNMT). Although the dust emitted from construction sources is significant, no specific regulation has been enacted with regard to it. Construction activities, however, need to comply with Article 73 in the EPL to protect the atmospheric environment.

4.3 Approving and Implementing Programs to Control, Reduce and Remedy Air Pollution

In 2016, the Prime Minister approved a national action plan for air quality management to 2020 with a vision to 2025, which hammered out specific targets and priority activities (Decision No. 985a/QD-TTg). With regard to the management and control of $PM_{2.5}$ pollution, the following aspects are given high priority: (i) development of regulations for guidance, assessment, identification and control; (ii) emission inventory development; and (iii) research on and application to determination of emission sources.

4.3.1 Traffic Emission Control

In urban areas, traffic emission control is one of the key tasks of environmental management agencies. Gas emission inspections for cars have been carried out since 1999 in Hanoi, Hai Phong, Da Nang and Ho Chi Minh City. In 2006, inspections carried out in these cities and Can Tho showed compliance with the Euro 2 standards. Following that, the inspections were expanded nationwide in July 1, 2008. In accordance with the roadmap, Vietnam continued to tighten and raise its emission standards to Euro 3 levels for motorcycles and Euro 4 levels for cars manufactured, assembled or imported after January 1, 2017 (Decision No. 49/2011/QĐ-TTg). By January 1, 2018, following the roadmap for a biofuels development scheme, RON 92 gasoline was replaced by RON95 (A95) gasoline (with less toxic emissions than A92) and E5 RON92 (E5) gasoline (biofuel) at the national scale (Decision No. 53/2012/QĐ-TTg, Report No. 255/TB-VPCP).

Additionally, the prime minister approved a project called "Environmental Pollution Control in Transportation Activities" in 2011 (Decision No. 855/QĐ-TTg), which focused on PM_{10} and $PM_{2.5}$ emitted by traffic in urban areas. Recently, Hanoi approved projects titled " Strengthening the management of road vehicles to reduce traffic congestion and environmental pollution in Hanoi in 2017-2020 with a vision to 2030" and "Anti-noise, anti-dust" in 2017. The deployment of public transport has been conducted largely in Hanoi and Ho Chi Minh City.

4.3.2 Construction Emission Control

Construction sites have popped up everywhere in urban areas in recent years, accompanied by increasing dust emissions from construction activities (land excavation at construction sites and roads, transportation of construction materials, dust from construction waste, etc.). Although, most activities such as covering construction sites, shielding transportation vehicles for construction materials, spraying water, washing roads, washing vehicles going to the construction sites, etc. are being applied, they have not been effective at preventing dust emissions from this source.

4.3.3 Industrial Emission Control

Air pollution from industry (i.e., industrial zones, industrial clusters, production establishments, handicraft villages, etc.) is being managed by supervising emission sources, relocating/limiting establishments causing serious environmental pollution and intensifying sanctions against those who violate legislation on environmental protection.

Vietnam nowadays focuses on controlling industries with high pollution emissions such as steel, chemical fertilizers, thermal power, cement, etc. by initial implementation. According to the regulations, those production facilities must register their industrial exhaust gas emission sources to MONRE, install automatic, continuous emission monitoring systems and transmit data in real time to DONRE. On the government side, MONRE is responsible for approval of emission source registrations, receiving monitoring data from DONRE and developing industrial exhaust gas emission inventories and databases (Decree No. 38/2015/NĐ-CP).

For establishments that have caused serious environmental pollution, since 2003 up to now, the Prime Minister has frequently approved a list of establishments nationwide to be relocated or required to apply pollution treatments (Decision No. 64/2003/QĐ-TTg). At the same time, Vietnam has also reviewed and supplemented regulations to restrict investment and developed a special control scheme for establishments with a high risk of environmental pollution. Additionally, in order to encourage enterprises to apply cleaner production technologies and to be involved in waste treatment, the Vietnamese government has also introduced preferential policies such as an import tax exemption policy for equipment and raw materials for waste treatment and promotion of research in and application to recycling, reuse and waste treatment (Decree No. 04/2009/NĐ-CP). However, sanctions for violations of the environmental protection law, including those that affect the atmospheric environment, have also been strengthened in terms of sanctioning forms and levels for industrial establishments (Decree No. 155/2016/NĐ-CP).

4.4 Maintaining and Enlarging Air Quality Monitoring Networks

In Vietnam, air quality monitoring was implemented from the 1990s up to now and continues to be maintained, promoted and managed for research, management and community information purposes. National and local monitoring programs have been implemented in urban areas, key economic zones, industrial zones, factories, production facilities and other places. Regular periodic sampling is done three to six times per year with more than 100 monitoring points for the national programs and six to 12 points for the local ones. In addition, automatic and continuous monitoring networks at the national and local scales have been investigated, installed and put into operation (Fig. 2).

The results of environmental monitoring at the national and local levels need to be stored in databases. From 2016, according to regulations, the periodical environmental monitoring results of provinces and cities must be reported to MONRE via CEM. At present, monitoring data mainly serve as input for reports by the environmental management agency and research projects upon request, and information for the community in various forms.

4.5 Involving Organizations and Communities

In cooperation with the Clean Air Initiatives of Asian Cities (CAI-ASIA), World Bank, Japan International Cooperation Agency (JICA), Korea Environment Corporation (KECO), Denmark's development cooperation (DANIDA), the Acid Deposition Monitoring Network in East Asia (EANET) and others, Vietnam has carried out urban air pollution control activities and expert exchanges. A recent key international project deserving mention has been "Institutional Development of Air Quality Management in Vietnam" sponsored by JICA (2013 to 2015). At the domestic scale, many organizations have been established and are active in research and publicity for environmental protection such as the Clean Air Network of Vietnam (VCAP), Center Green Innovation (GreenID) and Live and Learn Vietnam. The US Embassy in Vietnam has also installed $PM_{2.5}$ monitoring equipment at its consulate offices in Hanoi and Ho Chi Minh City.

4.6 Enhancing Public Awareness

Dissemination of information on air quality to the community has been implemented in many forms such as by radio and television, newspapers, electronic boards, websites and mobile applications. Since 2011, VEA has published data on air quality as an Air Quality Index (AQI) and corresponding health warnings for Hanoi, Phu Tho, Ha Long, Hue, Da Nang, Nha Trang and other cities on its website. At the province level, the US embassy and Hanoi have built monitoring networks and maintained a website and/or mobile applications dedicated to dissemination of air quality information online to the community.

Since citizens have become aware of the harmful effects of air pollution on health, they have an increasing desire for air environmental protection and pollution reduction, and many people have started taking action. In large cities, they have turned off their motorbikes at red traffic lights, participated in the Earth Hour program, saved energy, used electric/electromagnetic stoves instead of gas or coal stoves, bought $PM_{2.5}$ measurement/filter devices for their homes, worn masks and taken other steps.

5. Conclusions

In this article, we have presented the current state of $PM_{2.5}$ pollution in Vietnam and its mitigation. $PM_{2.5}$ pollution is generally high, exceeding the national limit on many days, especially in urban areas. The northern provinces in Vietnam are affected by seasonal variation, with higher $PM_{2.5}$ concentrations in winter than summer as a result of the local climate and LRT pollution. Local $PM_{2.5}$ emission sources vary among measurement sites and sampling periods but are mainly from traffic, industry, construction/soil, biomass burning and coal combustion. LRT pollution contributes a large amount to $PM_{2.5}$ in the northern provinces, especially Hanoi, via the north and northeast monsoons. Exposure to $PM_{2.5}$ has been shown to increase the rate of respiratory diseases and even deaths in Vietnam.

To mitigate $PM_{2.5}$ pollution, Vietnam has focused on designing an environmental regulatory system, developing comprehensive environmental laws and standards, approving and implementing programs to control, reduce and remedy environmental pollution, enlarging air pollution monitoring networks, involving organizations and communities and enhancing public awareness. As a result, the quality of the atmospheric environment has also improved somewhat over the past few years, showing certain effectiveness of the actions.

$PM_{2.5}$ pollution management, however, still remains insufficient in Vietnam. Currently, automatic, continuous monitoring networks and manual measurements of $PM_{2.5}$ are limited. Some automatic monitoring stations have insufficient funds for maintenance, resulting in unsatisfactory fulfillment of technical requirements, incomplete data or reliability and interrupted operation. As a result, $PM_{2.5}$ data remain insufficient for accurately assessing the status of $PM_{2.5}$ nationwide or providing a basis for appropriate solutions and policies. Regarding air environmental laws and technical standards, there are still some issues with higher limits for $PM_{2.5}$ (i.e., 50 μg/m^3 and 25 μg/m^3 for 24-hour average and yearly average, respectively) in comparison with international standards such as US EPA, observation methods, measurement equipment, etc. Furthermore, control and inventories of $PM_{2.5}$ emissions are still problematic since effective solutions and technologies for monitoring air pollution from each specific source are lacking.

In the future, Vietnam will need to continue to invest, manage and control $PM_{2.5}$ pollution in a more effective way. Research on and solutions and action to control $PM_{2.5}$ emission sources should be given a high priority. In addition to governmental environmental regulators, other stakeholders should be an important factor in implementation of environmental programs in Vietnam. Communities should receive updated environmental information formally, correctly and promptly so that they can take more effective actions to reduce environmental pollution and protect the public health.

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References

Bac, V. T., Lam, D. T., Thinh, N. T. H., Nhan, D. D., Quang, N. H. and Hien, P. D. (2003) Study variation of PM-10 air pollution at Lang Meteorological Station, Hanoi Coded: CS/02/04-06. *The VAEC - Annual Report for 2001–2002,* Vietnam Atomic Energy Commission.

Co, H. X., Dung, N. T., Kim-Oanh, N. T., Hang, N. T., Phuc, H. H. and Le, H. A. (2014) Levels and Composition of Ambient Particulate Matter at a Mountainous Rural Site in Northern Vietnam. *Aerosol and Air Quality Research*, 14(7), 1917–1928.

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. *Atmospheric Environment*, 44(3), 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. *Atmospheric Environment*, 44(31), 3761–3769.

Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope Ⅲ, C. A., Shin, H., Straif, K., Shaddick, G., Thomas, M., Dingenen, R. V., Donkelaar, A. V., Vos, T., Murray, C. J. L. and Forouzanfar, M. H. (2017) Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *The Lancet*, 389(10082), 1907–1918.

Dung Hai, C. and Kim-Oanh, N. T. (2013) Effects of local, regional meteorology and emission sources on mass and compositions of particulate matter in Hanoi. *Atmospheric Environment*, 78, 105–112.

Gatari, M. J., Boman, J., Wagner, A., Janhäll, S. and Isakson, J. (2006) Assessment of inorganic content of $PM_{2.5}$ particles sampled in a rural area north-east of Hanoi, Vietnam. *Science of The Total Environment*, 368(2), 675–685.

Hang, N. T. and Kim-Oanh, N. T. (2014) Source Apportionment for Particulate Matter Air Quality Management of a Mining Town in Quang Ninh, Vietnam. *Atmospheric Research,* 145–146, 214–215.

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. *Atmospheric Environment*, 36, 3473–3484.

Hien, P. D., Binh, N. T., Truong, Y., Ngo, N. T. and Sieu, L. N. (2001) Comparative receptor modeling study of TPS, PM_2 and PM_{2-10} in Ho Chi Minh City. *Atmospheric Environment*, 35, 2669–2678.

Hien, P. D., Bac, V. T. and Thinh, N. T. H. (2004) PMF receptor modeling of fine and coarse PM_{10} in air masses governing monsoon conditions in Hanoi, northern Vietnam. *Atmospheric Environment*, 38, 189–201.

Hong Van, N. P., Nga, T. T., Arai, H., Hosen, Y., Chiem, N. H. and Inubushi, K. (2014) Rice straw management by farmers in a triple rice production system in the Mekong Delta, Viet Nam. *Tropical Agriculture Development*, 58(4), 155–162.

Hopke, P. K., Cohen, D. D., Begum, B. A., Biswasc, S. K., Nid, B., Pandit, G. G., Santoso, M., Chung, Y. S., Davy, P., Markwitzh, A., Waheed, S., Siddique, N., Santos, F. L., Pabroa, P. C. B., Seneviratne, M. C. S., Wimolwattanapun, W., Bunprapob, S., Bac, V. T., Hien, P. D. and Markowiczo, A. (2008) Urban air quality in the Asian region. *Science of the Total Environment*, 404(1), 103-112.

Huong Giang, N. T. and Kim Oanh, N. T. (2014) Roadside levels and traffic emission rates of $PM_{2.5}$ and BTEX in Ho Chi Minh City, Vietnam. *Atmospheric Environment*, 94, 806-816.

Kim Oanh, N. T., 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 Lindgrenh, E. S. (2006) Particulate air pollution in six Asian cities: Spatial and temporal distributions, and associated sources. *Atmospheric Environment*, 40(18), 3367-3380.

Koplitz, S. N., Jacob, D. J., Sulprizio, M. P., Myllyvirta, L. and Reid, C. (2017) Burden of disease from rising coal-fired power plant emissions in *Southeast Asia. Environmental Science and Technology*, 51, 1467-1476.

Lasko, K., Vadrevu, K. P., Tran, T. V., Ellicott, E., Nguyen, T. N. T., Bui, Q. H. and Justice, C. (2017) Satellites may underestimate rice residue and associated burning emissions in Vietnam. *Environmental Research Letters*, 12(8), 85006.

Luong, L. M. T., Phung, D., Sly, P. D., Morawska, L. and Thai, P. K. (2016) The association between particulate air pollution and respiratory admissions among young children in Hanoi, Vietnam. *Science of the Total Environment*, 578, 249-255

Ministry of Natural Resources and Environment (MONRE) (2015) *National Environmental Report for 2011-2015*. Retrieved from http://cem.gov.vn (accessed 30 April 2018)

Ministry of Natural Resources and Environment (MONRE) (2016) *National Environmental Report: Air Environment.* Retrieved from http://cem.gov.vn (accessed 30 April 2018)

Nguyen, T. N. T., Ta, V. C., Le, T. H. and Mantovani, S. (2013) Particulate matter concentration estimation from satellite aerosol and meteorological parameters, data-driven approaches. *In:* Huynh, V., Denoeux, T., Tran, D., Le, A. and Pham, S. eds., *Knowledge and Systems Engineering. Advances in Intelligent Systems and Computing*, 244, 351-362.

Nguyen, T. N. T., Bui, Q. H., Pham, V. H., Luu, V. H., Man, D. C., Pham, N. H., Le, T. H. and Nguyen, T. T. (2015) Particulate matter concentration mapping from MODIS satellite data: a Vietnamese case study. *Environmental Research Letters*, 10(9), 95016.

Nhung, N. T. T., Schindler, C., Dien, T. M, Probst-Hensch, N., Perez, L. and Künzli, N. (2018) Acute effects of ambient air pollution on lower respiratory infections in Hanoi children: An eight-year time series study. *Environment International,* 110, 139-148.

Snider, G., Weagle, C. L., Murdymootoo, K. K., Ring, A., Ritchie, Y., Stone, E., Walsh, A., Akoshile, C., Anh, N. X., Balasubramanian, R., Brook, J., Qonitan, F. D., Dong, J., Griffith, D., He, K., Holben, B. N., Kahn, R. and Lagrosas, N. (2016) Variation in global chemical composition of $PM_{2.5}$: emerging results from SPARTAN. *Atmospheric Chemistry and Physics*, 16(15), 9629-9653.

Tran, T. V., Pham, V. H., Nguyen, T. N. T., Pham, X. T., Bui, Q. H., Nguyen, X. A. and Nguyen, T. T. (2018) Satellite aerosol optical depth over Vietnam—an analysis from VIIRS and CALIOP aerosol products. *In:* Vadrevu K., Ohara T., Justice C. (eds), *Land-Atmospheric Research Applications in South and Southeast Asia, Springer Remote Sensing/Photogrammetry.* Springer, Cham, 499-522.

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