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ORIGINAL PAPER

Chemical Compositions of $PM_{2.5}$ Emitted from Diesel Trucks and Construction Equipment

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Abstract
This study reported the chemical compositions of $PM_{2.5}$ for seven kinds of China IV diesel trucks and three kinds of stage II construction equipment. Filter samples were directly collected at the tailpipe with a dilution system. Twenty elements (Al, Si, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Cd, Sn, Sb, Ba and Pb), water-soluble ions (WSIs) including NH_4^+, K^+, Ca^{2+}, Cl^-, NO_3^- and SO_4^{2-}, and carbonaceous species were analyzed and characterized. The uncertainties of these species were also estimated. Overall, the highest proportion of $PM_{2.5}$ was contributed by carbonaceous matter (OC and EC), accounting for 46.4 and 38.5% for trucks and construction equipment, respectively. The EC/OC ratios were higher than 1, with lowest in light-duty diesel trucks (LDDTs) as 1.4 ± 0.2 and highest in excavators as 5.1 ± 0.3. Similarities and differences were compared among source profiles using the residual (R)/uncertainty (U) ratios. Also Pearson's correlation coefficients among the chemical compositions were analyzed to determine the relationships between the various chemical components. In addition, the source profiles of diesel trucks and construction equipment in our study were compared with those reported by other studies in recent years from China. Variations were observed in the results due to uncontrolled factors such as operating conditions, fuel quality and sampling measurements. To assess these uncertainties, better knowledge of local source profiles and more elaborate measurements are needed for future research.

Keywords Chemical compositions · PM source profile · Diesel exhaust

1 Introduction

Fine particulate matter ($PM_{2.5}$) pollution has been a great concern due to its adverse influence on environmental problems, including haze formation (Wang et al. 2016; Huang et al. 2014) and climate change (Wang et al. 2014), as well as public health such as cardiovascular disease and cancer (Brook et al. 2010; West et al. 2016). Previous studies have shown that mobile sources contributed 12.6–44% to PM pollution, which is predominantly from diesel exhaust (Huang et al. 2015; Cai et al. 2016; Cui et al. 2017; Reff et al. 2009). In China, diesel vehicles are responsible for 99% of vehicle emissions although they only account for 15.2% of on-road vehicles (Deng et al. 2016). In addition, the non-road diesel mobile source plays an important role in economic and social development. Compared with the motor vehicles, it has higher emissions due to inefficiency of the supervision and management in China (Ma et al. 2017). The non-road diesel exhaust becomes another important source to the regional air pollution.

China started to implement the vehicle emission control programs in 1990s, lagging more than 20 years behind developed countries (Wang and Yu 2017; Yue et al. 2015). A series of emission standards (from the China I to China V) have been promulgated for on-road diesel exhaust since then. For the non-road diesel exhaust, the first emission standard was adopted in 2007 (stage I), 7 years later than that in the US. The stage III was adopted in April of 2016, following the new amended Air Pollution Law (Wu et al. 2017).

$PM_{2.5}$ emitted by diesel exhaust consists of a mixture of chemical constituents. For instance, organic and elemental carbon is the byproduct of incomplete fuel combustion, which contribute to light-absorbing and radiation budget (Wang and Yu 2017); water-soluble ions (WSIs) are formed by inorganic contaminants in fuel and engine wear, contributing to the acidity of aerosols (Mkoma et al. 2014);

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Elements such as Cu, Ba, Sn and Sb are important components which are related to brake wear and lubricant oil (Pant et al. 2015).

Source profiles (fingerprints) are essential for source apportionment research (Watson and Chow 2001; Watson et al. 2001). The fingerprints of diesel exhaust are needed as input data for receptor models and source-oriented models (Zhang et al. 2017; Simon et al. 2010). Diesel exhaust emissions have been investigated by different approaches, including tunnel tests, roadside tests, classic dynamometer measurements and on-road tests using portable emission measurement system (PEMS) (Zhang et al. 2016; Chen et al. 2017; Cheng et al. 2010; Cui et al. 2016, 2017; Wang et al. 2003; Wu et al. 2016). For example, USEPA SPECIATE database contains speciation profiles for a comprehensive list of emission sources. The latest version (SPECIATE 4.5) identified many mobile source emissions that contain diesel, gasoline and future fuels (e.g., low sulfur diesel, biodiesel) (Hsu et al. 2016). Watson et al. (2001) collected the vehicle exhaust samples near the diesel bus terminals in Colorado and found that carbon fraction accounted over 95% in $PM_{2.5}$. Popovicheva et al. (2017) tested a heavy diesel engine in different driving conditions using alternative diesel fuels. Cheng et al. (2010) measured tunnel and roadside PM emissions of on-road vehicles in Hong Kong during 2003, and calculated emission factor (EF) of diesel and non-diesel-fueled vehicles. Wu et al. (2016) analyzed emission characteristics of diesel truck emissions in Beijing, and compared differences between profiles of vehicle emission standard of China III and those of China IV. Cui et al. (2016) characterized $PM_{2.5}$ emitted in two urban tunnels in Yantai and drafted the source profiles of gasoline and diesel-fueled vehicles. Cui et al. (2017) tested non-road and on-road diesel vehicles of a wide range of emission standards and operation modes (pre-stage 1 to stage 2; China II to China IV) using an improved PEMS.

To date, source profiles of diesel exhaust are still limited in China. Many studies use non-local source profiles when local profiles are unavailable (Zheng et al. 2013; Mei et al. 2014; Pirovano et al. 2015; Taiwo et al. 2014) and mostly only focused on the on-road diesel exhaust. However, the non-road mobile source, such as construction equipment, should not be overlooked due to its low technical level, long service life and poor fuel quality (Ma et al. 2017). Cai et al. (2016) have reported that the source apportionment model results were subject to the uncertainties from using non-local source profiles, resulting in a great variabilities in the model results even in the same city (Zhang et al. 2017). Thus, developing local source profiles are crucial for accurate source apportionment and modeling assessment.

Our research aims to: (1) characterize the chemical compositions of diesel-fueled truck and construction equipment; (2) establish the source profiles for receptor modeling to guide the pollution control strategy. The knowledge on source profiles is intended to be beneficial in improving chemical component emission inventories and the source apportionment models.

2 Methodology

The primary $PM_{2.5}$ emissions were measured from seven on-road China IV diesel trucks and three Stage II construction equipments. The tested diesel trucks were divided into two groups based on the vehicle weights: three light-duty diesel trucks (LDDTs, less than 4.5t) and four heavy-duty diesel trucks (HDDTs, more than 12t). Three sets of common construction equipment were selected including crane, loader and excavator. Detailed information for the tested vehicles is shown in Table 1.

Two kinds of filters were used to collect $PM_{2.5}$ samples directly at the tailpipe with a dilution system, with three parallels. These filters were used for $PM_{2.5}$ weight measurement and chemical analysis at laboratory. Teflon-membrane filters were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) for twenty elements including Al, Si, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Cd, Sn, Sb, Ba and Pb. Quartz-fiber filters were analyzed for NH_4^+, K^+, Ca^{2+}, Cl^-,

Table 1 Information of the tested trucks and construction equipment

ID	Vehicle type	Model year	Emission standard	Power (kW)	Weights (kg)
1	LDDT	2011	China IV	80	4495
2		2013	China IV	68	3150
3		2014	China IV	88	4495
4	HDDT	2011	China IV	101	15,400
5		2013	China IV	115	13,590
6		2013	China IV	121	15,360
7		2012	China IV	101	15,360
8	Crane	2009	Stage II	162	28,170
9	Loader	2009	Stage II	184	25,000
10	Excavator	2008	Stage II	169	13,800

NO_3^- and SO_4^{2-} using ion chromatography. OC and EC were analyzed following the IMPROVE thermal/optical reflectance (TOR) protocol. Detailed information can be referred to Ren et al. (2014). The measurements were blank corrected using field blanks that were handled and stored in the same manner as the samples. The data quality control methodology applied in this study is same with Liu et al. (2017). The composite source profiles were obtained by determining the component mass fractions of $PM_{2.5}$ in samples for each vehicle type. The standard deviations (SD) were also calculated for the parallel samples. Overall uncertainty can be illustrated as the sum of population and measurement uncertainty (Chen et al. 2017; USEPA 2013). The uncertainties in this study were estimated by the equation below:

$$U_c = F_c\left[\left(\frac{\mathrm{MDL}}{M_c}\right)^2 + \mathrm{CV}^2\right]^{0.5}, \quad (1)$$

where U_c refers to the uncertainty of measured component c in source profile; F_c is mass fractions of the component c; M_c is the measured mass of each component. MDL is the method detection limit (MDL) of the analysis instruments; CV refers to the coefficient of variation, which is SD/F_c.

3 Results and Discussion

3.1 Chemical Compositions

The main compositions of diesel trucks and construction equipment are shown in Table 2 and Fig. 1. The measured masses were 44.9 ± 7.9, 59.3 ± 12.8, 45.8 ± 11.2% of $PM_{2.5}$ for tested LDDTs, HDDTs and construction equipment, respectively. The discrepancy of mass fractions may be attributed to the engine model, fuel quality, unmeasured species and analytical errors such as distribution of OC and EC by the TOR method (Cui et al. 2017; Chow et al. 2015).

Table 2 The main chemical compositions of diesel trucks and construction equipment

Vehicle type	LDDT		HDDT		Crane		Loader		Excavator	
Species	F_c	U_c	F_c	U_c	F_c	U_c	F_c	U_c	F_c	U_c
OC	16.45	2.64	16.91	4.72	12.53	1.88	8.69	1.71	6.81	2.37
EC	23.63	2.66	30.81	5.82	23.54	3.74	22.81	3.59	35.03	5.10
Cl^-	0.28	0.02	1.68	0.79	0.91	1.04	1.08	0.65	1.39	1.23
SO_4^{2-}	1.11	0.51	1.14	0.63	1.98	1.14	2.25	1.13	2.36	1.82
NO_3^-	0.06	0.03	0.42	0.15	0.89	0.63	0.27	0.23	0.43	0.51
NH_4^+	0.04	0.02	0.19	0.87	0.17	0.13	0.32	0.11	0.12	0.09
K^+	0.05	0.01	0.29	0.12	0.15	0.04	0.08	0.06	0.14	0.07
Ca^{2+}	0.07	0.01	0.82	0.19	0.08	0.05	0.10	0.05	0.75	0.30
Al	0.66	0.18	1.17	0.53	0.55	0.29	0.16	0.72	1.35	0.22
Si	0.64	0.25	0.91	0.33	0.33	0.08	0.57	0.21	0.85	0.38
K	0.08	0.01	0.43	0.41	0.21	0.05	0.16	0.03	0.20	0.07
Ca	0.33	0.08	0.45	0.57	0.33	0.58	0.18	0.13	0.26	0.13
Ti	0.21	0.09	0.54	0.46	0.34	0.09	0.31	0.03	0.52	0.49
Sr	0.00	0.00	0.04	0.05	0.00	0.00	0.00	0.00	0.04	0.01
V	0.00	0.00	0.04	0.04	0.01	0.00	0.01	0.00	0.03	0.01
Cr	0.03	0.02	0.05	0.03	0.06	0.02	0.01	0.00	0.03	0.00
Mn	0.01	0.01	0.03	0.02	0.01	0.00	0.00	0.00	0.01	0.00
Fe	1.17	0.30	2.95	1.71	2.29	0.37	1.98	0.16	3.37	0.89
Co	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ni	0.00	0.00	0.01	0.01	0.02	0.00	0.00	0.00	0.01	0.00
Cu	0.05	0.04	0.07	0.11	0.03	0.02	0.02	0.01	0.04	0.00
Zn	0.03	0.01	0.15	0.21	0.04	0.02	0.02	0.00	0.05	0.01
As	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01
Cd	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sn	0.00	0.00	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.00
Sb	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.08	0.07	0.01	0.01	0.01	0.00	0.09	0.02
Pb	0.00	0.00	0.05	0.07	0.00	0.00	0.00	0.00	0.01	0.00

F_c is the mass fractions of component c, U_c is the related uncertainties

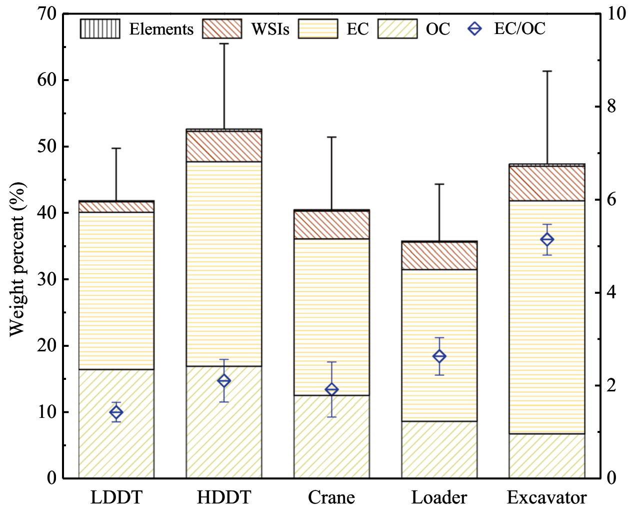

Fig. 1 Major components of $PM_{2.5}$ source profiles for light-duty diesel trucks (LDDT), heavy-duty diesel trucks (HDDT), crane, loader and excavator. Error bars of the column represent the total propagated error calculated from the uncertainties for each chemical component. The rhombs represent the ratios of EC/OC

As shown in Fig. 1, carbon fractions (OC and EC) were the dominant component in source profiles of diesel exhaust. OC abundances were 10.6–36.3% while EC abundances were 20.3–40.8%. The results were consistent with previous studies. For example, Zhang et al. (2015) measured the real-world $PM_{2.5}$ emissions of HDDTs (pre-stage and stage I) using a portable emissions measurement system (PEMS), reporting that carbon fractions contributed 89% of $PM_{2.5}$ mass. Cui et al. (2017) reported that OC and EC proportions ranged from 18.1 to 84.6% in PM measured from five trucks and six excavators. The relationship between EC and OC concentrations can be used to evaluate the sources of carbonaceous aerosols (Tao et al. 2014; Turpin and Huntzicker 1995) In vehicle exhaust research, it can also indicate the effectiveness of the diesel oxidation catalysts (DOC), which remove the OC fraction via oxidation (Cheng et al. 2015). In this study, EC/OC ratios were performed to characterize the emissions of diesel exhaust. The EC/OC ratios were higher than 1 and ranged from 1.4 ± 0.2 for LDDTs to 5.1 ± 0.3 for excavators. The results were similar with Wu et al. (2016), who reported that EC/OC mass ratios were 0.20–3.06 for the China III whereas 2.52–6.94 for the China IV diesel trucks. Cui et al. (2017) reported the OC/EC ratios of different operation modes for excavators; the average ratios were 1.57, 0.57 and 2.38 during idling, moving and working.

The WSIs fractions ranged from 0.9 to 7.8% and dominated by SO_4^{2-} and NO_3^-. The highest WSIs abundances were found in source profiles of excavator (averaged 5.2%) while the lowest in LDDTs (averaged 1.6%). For the LDDTs, SO_4^{2-} was the most abundant ions, contributing 70.0% of the WSIs. For the HDDTs, Cl^-, SO_4^{2-} and Ca^{2+} contributed 36.9, 25.2, and 18.1% of the WSIs, respectively. Wu et al. (2016) reported that the WSIs fractions emitted from China III and China IV diesel trucks were dominated by SO_4^{2-}, NO_3^- and Ca^{2+}; the result is consistent with our results. It is notable that SO_4^{2-} abundances emitted from construction equipment were 1.7–2.1 times higher than that from diesel trucks. This may be attributed to the insufficient quality of non-road diesel fuel. The quality standards for non-road diesel fuels are formulated separately in China, lagging behind the on-road ones (Wu et al. 2017). The actual sulfur content in construction equipment fuels may be higher than that in truck fuels tested in this study.

Elements are important components in source profiles and can be used as tracers although they only account for a small fraction of the $PM_{2.5}$ mass emissions. For vehicle exhaust, Cu, Zn, Ba and Br have been widely applied as trace compositions in source apportionment studies (Pant et al. 2015; Zhang et al. 2017). The relatively dominant elements were Fe, Cu, Zn, Ba and Cr. Previous studies have reported that Cu and Zn were related to tire wear, brake wear and lubricating oil; Ba and Cr derived from the brake wear; Fe accounted for large proportion of elements in diesel fuel (Pant et al. 2015; Adamiec et al. 2016; Godoy et al. 2009; Salvador et al. 2007). In this study, Pb abundances (0.05 ± 0.07%) had large variations from HDDTs and relatively higher than that in other vehicles. The proportion of Pb emitted from vehicles is still remarkable although its direct emissions have been forbidden since 2003 in China. Figure 2 shows the elemental profiles from diesel exhausts. These profiles are usually applied to identify specific sources in receptor models such as CMB and PMF.

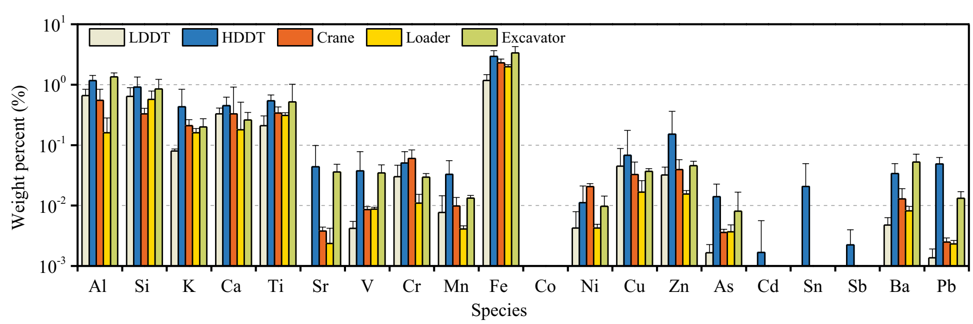

Fig. 2 Elemental profiles of $PM_{2.5}$ for light-duty diesel trucks (LDDT), heavy-duty diesel trucks (HDDT), crane, loader and excavator. Error bars of the column represent the uncertainties for each chemical species

3.2 Correlations Among $PM_{2.5}$ Species

Pearson's correlation analysis for chemical species in source profiles has been conducted in previous studies (Mkoma et al. 2014; Pei et al. 2016; Shen et al. 2016). In this study, Pearson's correlation coefficients (R) were calculated for chemical compositions of diesel exhaust, with the p value threshold of 0.05. As shown in Table 3, EC, SO_4^{2-}, NO_3^-, K^+ and Cl^- abundances showed moderate correlations with $0.5 < R < 0.8$, mainly derived from the fuel combustion. OC and EC were not strongly correlated for construction equipment while they were correlated for trucks, with $R = 0.63$. Pb was strongly correlated with Sr and Cd with the R values of 0.92 and 0.88, which was consistent with the research of Wu et al. 2016. Similarly, Ca, Ba and V had significant correlations ($0.81 < R < 0.85$), while V was also correlated with Fe ($R = 0.83$). Al and Si showed correlations with V, As and Fe, whereas weak correlations with Cr, Mn, Sb and Pb. Wu et al. (2016) had observed that most of elements, including Ti, V, Cr, Mn, Co, Ni, Cu, Ga, As, Sr, Pb, and U, were well correlated for emissions of China III and China IV diesel trucks.

3.3 Similarities and Differences Between Source Profiles

Previous studies commonly compare the profiles with each other by calculating the coefficient of divergence (COD) to determine whether any two profiles could be considered to be similar (Zhang et al. 2014; Chen et al. 2017; Kong et al. 2014). However, the COD values were insufficient, as only chemical abundances are considered in the calculation. Uncertainties in the source profiles are needed to be considered as well.

Statistical measures used in this part were same as Chow et al. (2003), who established a profile-compositing methodology to evaluate similarities and differences for geological sources from San Joaquin Valley. Pearson's correlation coefficient ($p < 0.05$) quantifies the strength of statistical relationship between chemical abundances of paired profiles. R/U ratios (the distribution of weighted differences, $R/U = (F_{c1} - F_{c2})/(U_{c1}^2 + U_{c2}^2)^{0.5}$) were applied to determine the differences between certain species from paired profiles. Chemical abundances with R/U higher than three times of standard deviations (3σ) were considered to be different. The correlation coefficient, R/U ratios and its 3σ of each species between profiles were summarized in Table 3. Ten paired source profiles were compared. All the correlation coefficients exceed 0.9, indicating good linear dependent between species of paired profiles. For the HDDTs profile, R/U ratios exceeded 3σ for Ca^{2+} compared with other profiles. Ca^{2+} fractions ($0.82 \pm 0.19\%$) emitted from HDDTs were relatively high. The significant difference of OC abundances was found between construction equipment and truck exhaust, with R/U ratios ranged from 2.46 to 4.54. Chemicals with R/U ratios > 3 in one or more of the comparisons were Sr, V, Co, Ni, Mn and Pb. The R/U ratios could have been affected by both measured uncertainty and natural variability in abundances from different samples. It could be used to quantify the similarities and differences among source profiles and to select input chemicals for CMB model.

3.4 Comparison of Source Profiles for Diesel Exhaust with Other Studies

Table 4 summarizes the composite profiles of diesel trucks and construction equipment in our study, as well as profiles reported by other studies in recent years in China.

For the diesel trucks, total carbon fraction was the dominant component, accounting for 36.8–87.1%. EC fraction tested in this study was consistent with that reported by Cui et al. (2017). WSIs abundances ranged from 1.3 to 11.7%. NO_3^- and SO_4^{2-} levels from tunnel were higher tested by Cui et al. (2016). The tunnel with a lot of traffic has undoubtedly more extensive high-temperature anthropogenic emissions of the precursor gas such as NO_x and SO_2. As a result, the ions are likely to be primarily emitted from fuel burning and derived from gas-to-particle conversion (Mkoma et al. 2014). Element fractions contributed 0.5–7.6% of the $PM_{2.5}$ and dominated by Fe, except for the tunnel test study. Ca was the most abundant species in tunnel test profile, which essentially attributable to soil/mineral dust dispersal.

To date, there was only one study about the source profiles of non-road diesel vehicle (excavators) exhaust in China (Cui et al. 2017). The $PM_{2.5}$ emitted from construction equipment was dominated by carbon fraction, followed by WSIs and elements. The OC abundance tested in this study was lower than that reported by Cui et al. (2017), while the Fe abundance was higher. The differences could be attributed to several factors such as fuel quality, test condition and so on. Besides, the source profiles of construction equipment established in this study were comprehensive by compositing different vehicle types of crane, loader and excavator.

The USEPA SPECIATE database is currently the most comprehensive collection of source profiles available, containing over 3000 PM profiles from the literature, and update to version 4.5 in September 2016. The diesel exhaust source profiles of SPECIATE 4.5 database were also extracted. These profiles were averaged (compute the median) together based on source category to create a composite profile, following the method of Reff et al. (2009). The detailed information of these profiles can be found in our previous study (Liu et al. 2017). As shown in Table 5, it is worth noting that carbon fraction in SPECIATE source profile is much higher than that in this study. This may be attributed to the quality of PM source

Table 3 Pearson's correlation coefficients (R) for chemical compositions of diesel exhaust in this study

	OC	EC	Cl^-	SO_4^{2-}	NO_3^-	K^+	Al	Si	Ca	Sr	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	As	Cd	Sn	Sb	Ba	Pb
OC	1.00																							
EC	0.63	1.00																						
Cl^-	0.30	0.59	1.00																					
SO_4^{2-}	0.27	0.50	0.65	1.00																				
NO_3^-	0.07	0.61	0.77	0.43	1.00																			
K^+	0.59	0.73	0.66	0.44	0.10	1.00																		
Al	0.05	− 0.05	0.35	0.04	0.63	− 0.21	1.00																	
Si	0.07	0.48	0.60	0.20	0.48	0.26	0.58	1.00																
Ca	0.19	0.57	0.78	0.62	0.55	0.67	0.46	0.52	1.00															
Sr	0.36	0.19	0.71	0.31	0.43	0.64	0.09	0.38	0.48	1.00														
V	0.13	0.12	0.54	0.19	0.85	0.00	0.71	0.53	0.82	0.32	1.00													
Cr	0.44	0.55	0.69	0.40	0.44	0.56	0.25	0.13	0.72	0.36	0.37	1.00												
Mn	0.63	0.52	0.67	0.33	0.28	0.82	0.18	0.21	0.62	0.66	0.23	0.42	1.00											
Fe	0.34	0.09	0.49	0.42	0.79	− 0.07	0.65	0.61	0.62	0.10	0.83	0.40	0.10	1.00										
Co	0.26	0.12	0.40	0.70	0.28	0.31	0.10	0.15	0.72	0.20	0.35	0.59	0.20	0.60	1.00									
Ni	0.23	− 0.29	0.03	− 0.05	0.41	− 0.33	0.63	0.19	0.24	− 0.03	0.63	− 0.08	0.11	0.65	0.17	1.00								
Cu	0.06	0.01	0.27	0.04	0.48	− 0.03	0.79	0.16	0.35	0.08	0.67	0.14	0.43	0.65	0.19	0.80	1.00							
Zn	0.34	0.04	0.15	0.70	0.03	0.21	− 0.15	− 0.23	0.39	0.00	0.04	0.37	0.08	0.33	0.86	0.01	0.04	1.00						
As	0.19	0.50	0.87	0.45	0.88	0.39	0.51	0.64	0.72	0.55	0.79	0.74	0.46	0.68	0.39	0.24	0.40	0.14	1.00					
Cd	0.47	0.18	0.44	0.20	− 0.05	0.68	− 0.26	0.19	0.21	0.86	− 0.19	0.19	0.64	− 0.35	0.02	− 0.31	− 0.21	− 0.01	0.16	1.00				
Sn	0.55	0.47	0.36	0.27	− 0.24	0.89	− 0.49	0.03	0.31	0.62	− 0.35	0.27	0.68	− 0.45	0.11	− 0.50	− 0.33	0.15	0.04	0.85	1.00			
Sb	0.41	0.47	0.65	0.33	0.47	0.62	0.24	0.22	0.54	0.64	0.46	0.50	0.80	0.32	0.28	0.22	0.47	0.27	0.68	0.49	0.47	1.00		
Ba	0.15	0.12	0.67	0.57	0.71	0.33	0.44	0.37	0.80	0.59	0.80	0.49	0.46	0.80	0.74	0.47	0.52	0.47	0.72	0.19	0.06	0.60	1.00	
Pb	0.35	0.11	0.52	0.20	0.21	0.59	0.08	0.30	0.39	0.92	0.22	0.17	0.76	0.02	0.15	0.13	0.23	0.01	0.35	0.88	0.64	0.67	0.52	1.00

Table 4 *R*/*U* ratios of each chemical species between paired source profiles

Species	*R*/*U*									
	LDDT/HDDT	LDDT/crane	LDDT/loader	LDDT/excavator	HDDT/crane	HDDT/loader	HDDT/excavator	Crane/loader	Crane/excavator	Loader/excavator
OC	0.08	1.21	2.46	2.72	3.60	4.40	4.54	1.51	1.89	0.65
EC	1.12	0.02	0.18	1.98	1.05	1.17	0.54	0.14	1.81	1.96
Cl^-	1.77	0.61	1.24	0.91	0.59	0.58	0.20	0.14	0.30	0.22
SO_4^{2-}	0.04	0.70	0.92	0.66	0.64	0.85	0.63	0.17	0.18	0.05
NO_3^-	2.33	1.32	0.89	0.72	0.73	0.54	0.01	0.93	0.58	0.28
NH_4^+	0.18	0.98	2.45	0.85	0.03	0.14	0.09	0.87	0.34	1.43
K^+	2.07	2.65	0.48	1.22	1.15	1.66	1.09	1.11	0.12	0.69
Ca^{2+}	3.87	0.21	0.65	2.25	3.68	3.58	0.19	0.30	2.18	2.11
Al	0.00	0.35	0.46	0.00	0.55	0.70	0.01	0.50	3.03	1.98
Si	1.16	2.60	1.59	2.44	0.82	0.90	0.48	0.69	1.98	2.07
K	0.85	2.44	2.96	1.67	0.52	0.64	0.54	0.76	0.08	0.49
Ca	1.98	1.69	2.49	2.46	1.27	1.41	0.62	0.22	1.85	1.98
Ti	0.70	0.98	1.03	0.61	0.43	0.49	0.04	0.26	0.35	0.41
Sr	0.79	4.65	0.84	2.82	0.73	0.76	0.14	0.72	2.58	2.67
V	0.82	2.66	3.16	2.46	0.71	0.71	0.06	0.13	2.11	2.11
Cr	0.65	1.06	1.10	0.03	0.26	1.44	0.77	2.10	1.31	2.98
Mn	1.06	0.28	0.52	0.80	1.00	1.27	0.86	1.52	0.86	6.10
Fe	1.02	2.38	2.38	2.34	0.37	0.56	0.22	0.78	1.11	1.53
Co	0.84	2.08	0.35	1.55	0.33	0.95	0.03	9.29	0.70	1.89
Ni	0.66	3.66	0.00	0.92	0.92	0.70	0.13	6.27	2.04	1.17
Cu	0.20	0.26	0.65	0.19	0.32	0.47	0.29	0.74	0.21	2.03
Zn	0.57	0.34	1.43	0.96	0.53	0.65	0.50	1.31	0.31	3.50
As	1.43	2.60	1.61	0.74	1.21	1.19	0.49	0.07	0.51	0.50
Cd	0.42	2.87	2.29	0.60	0.42	0.42	0.40	0.05	0.45	0.44
Sn	0.71	1.39	1.40	2.17	0.70	0.70	0.70	0.76	0.29	1.93
Sb	1.27	1.44	1.48	1.89	1.24	1.24	0.75	0.37	1.76	1.79
Ba	0.44	1.29	1.59	2.58	0.32	0.39	0.27	0.75	2.04	2.40
Pb	0.65	1.63	1.52	3.10	0.63	0.63	0.49	0.32	2.82	2.87
3σ	2.49	3.43	2.58	2.79	2.52	2.74	2.51	5.93	2.79	3.81

Table 5 Comparison of composite source profiles of diesel truck and construction equipment in different studies of China

Types	Diesel trucks								Construction equipment	
Methods	On-board	On-board	On-board	On-board	On-board	Dynamometer	Tunnel test	Composite	On-board	On-board
Reference	This study	Cui et al. (2017)	Wu et al. (2016)	Zhang et al. (2015)	Zhang et al. (2016)	Chiang et al. (2012)	Cui et al. (2016)	SPECIATE4.5	This study	Cui et al. (2017)
OC	16.832	9.89	31.8	–	54.415	24.503	27.2	33.497	11.342	39.2
EC	29.617	26.9	55.3	60.088	19.391	47.682	39.5	49.799	27.127	33.3
Cl^-	0.745	0.11	0.247	0.553	1.173	0.002	1.06	0.041	1.129	0.11
SO_4^{2-}	1.122	3.27	0.529	1.096	0.543	0.455	4.8	2.260	4.527	3.263
NO_3^-	0.182	1.08	0.529	0.631	1.428	0.542	3.81	0.199	0.864	1.076
NH_4^+	0.091	0.215	0.188	0.135	0.28	0.273	2.06	0.736	0.879	0.215
K^+	0.129	–	–	0.322	–	0.025	–	0.020	0.242	–
Ca^{2+}	0.322	–	–	0.734	0.515	0.075	–	–	0.313	–
K	0.368	0.197	–	–	0.043	0.319	0.872	0.018	0.19	0.029
Ca	0.413	0.241	–	–	0.006	0.752	5.69	0.376	0.249	0.212
Ti	0.487	0.01	0.145	0.159	–	0	0.206	0.000	0.39	0.011
Sr	0.037	–	–	–	0.011	0	–	0.000	0.014	–
V	0.032	0.001	0.001	–	0.004	0.008	0.008	–	0.017	0
Cr	0.047	0.035	0.011	0.105	0	0.028	0.013	0.001	0.033	0.038
Mn	0.028	0.013	0.002	0.071	0.017	0.059	0.064	0.001	0.009	0.009
Fe	2.649	0.815	0.247	0.653	0.021	0.596	0.5	0.275	2.546	0.276
Co	0	0.001	0	–	0.1	0.009	0.002	0.002	0	0.005
Ni	0.01	0.015	0.002	0.225	0.001	0.058	–	0.003	0.012	0.006
Cu	0.064	0.042	0.004	0.032	0.003	0.029	0.013	0.006	0.029	0.107
Zn	0.131	0.027	0.076	0.035	0.017	0.118	0.213	0.108	0.033	0.111
As	0.012	–	–	–	0.189	0.008	–	–	0.005	–
Cd	0.001	–	–	–	0.001	0.004	–	0.000	0	–
Sn	0.017	–	–	–	0.004	0	–		0.001	–
Sb	0.002	–	–	–	0	0.024	–	0.004	0	–
Ba	0.071	–	–	0.035	0.035	0.064	–	0.017	0.038	–
Pb	0.041	0.011	0.005	–	0.025	0.05	0.008	–	0.006	0.01

profiles of diesel exhaust (over 90% were established before 2008) in SPECIATE; the fuel, lubricating oil and engine technology have been updated in recent years.

4 Conclusions

This study reported the chemical compositions of $PM_{2.5}$ source profiles for six China IV diesel trucks and three stage II construction equipment. The highest proportion of $PM_{2.5}$ was contributed by carbonaceous matter (OC and EC), accounting for 46.4 and 38.5% for trucks and construction equipment, respectively. Similarly, WSIs accounted for 2.1 and 7.4%, and the tested total elements accounted for approximately 4.4 and 3.6% of the $PM_{2.5}$. EC/OC ratios were performed to characterize the emissions of diesel exhaust. The EC/OC ratios were higher than 1 and ranged from 1.4 ± 0.2 for LDDTs to 5.1 ± 0.3 for excavators.

Similarities and differences were compared among source profiles using *R*/*U* ratios. Chemicals with *R*/*U* ratios > 3 in one or more of the comparisons were Sr, V, Co, Ni, Mn and Pb. The *R*/*U* ratios could be affected by both measured uncertainty and natural variability in abundances from different samples. It could be also used to select input chemicals for CMB model.

To understand the relationships between the various chemical components, Pearson's correlation coefficients among the chemicals were analyzed. Some chemical species showed correlations. For example, EC, SO_4^{2-}, NO_3^- and Cl^- were moderately correlated. OC and EC were not strongly correlated for construction equipment whereas they were correlated for trucks. Pb showed strong correlations with Sr and Cd with the *R* values of 0.91 and 0.88.

The composite profiles of diesel trucks and construction equipment in our study was compared with that reported by SPECIATE database and other studies in recent years from China. However, variations were observed in the results due to uncontrolled factors such as operating conditions, fuel quality and sampling measurements. To assess these uncertainties, better knowledge of local source profiles and more elaborate measurements are needed for future research.

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Compliance with Ethical Standards

Conflict of interest The authors declare no competing financial interest.

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