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Atmospheric Chemistry and Physics Discussions

Measurement report: Chemical characteristics of $PM_{2.5}$ during typical biomass burning season at an agricultural site of the North China Plain

Linlin Liang[1], Guenter Engling[2,3], Chang Liu[1], Wanyun Xu[1], Xuyan Liu[4], Yuan Cheng[5], Zhenyu Du[6], Gen Zhang[1], Junying Sun[1], Xiaoye Zhang[1]

[1] State Key Laboratory of Severe Weather & Key Laboratory for Atmospheric Chemistry, Chinese Academy of Meteorological Sciences, Beijing 100081, China

[2] Division of Atmospheric Sciences, Desert Research Institute, Reno, NV 89512, USA

[3] Now at: California Air Resources Board, El Monte, CA 91731, USA

[4] National Satellite Meteorological Center, Beijing 100081, China

[5] School of Environment, Harbin Institute of Technology, Harbin 150001, China

[6] National Research Center for Environmental Analysis and Measurement, Beijing 100029 China

Abstract:

Biomass burning (BB) activities are ubiquitous in China, especially in North China, where there is an enormous rural population and winter heating custom. BB tracers (i.e., levoglucosan (LG), mannosan (MN) and potassium (K^+)), as well as other chemical components were quantified at a rural site (Gucheng, GC) in North China from 15 October to 30 November, during a transition heating season, when the field burning of agricultural residues was becoming intense. The measured daily average concentrations of LG, MN and K^+ in $PM_{2.5}$ during this study were 0.79 ± 0.75 μg m^{-3}, 0.03 ± 0.03 μg m^{-3} and 1.52 ± 0.62 μg m^{-3}, respectively. Carbonaceous components and BB tracers showed higher levels at nighttime than daytime, while secondary inorganic ions were enhanced during daytime. An episode with high levels of BB tracers was encountered at the end of October, 2016, with high LG at 4.37 μg m^{-3}. Based on the comparison of chemical components during different BB pollution periods, it appeared that biomass combustion can obviously elevate carbonaceous components levels, whereas no essentially effect on secondary inorganic aerosols in the ambient air. Moreover, the LG/MN ratios during different BB pollution periods remained at high values (in the range of 18.3-24.9), however, the LG/K^+ ratio was significantly elevated during the intensive BB pollution period (1.67) when air temperatures decreasing, substantially higher than in other BB periods (averaged at 0.47).

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***Keywords*:** Biomass burning; Organic tracers; Levoglucosan; Mannosan; Potassium

1. Introduction

Particulate air pollution is attracting more and more concerns in China because of their obvious adverse impact on visibility reduction, as well as health implication and regional or global climate change (Kanakidou et al., 2009; Pope and Dockery, 2006; Chen et al., 2017). Carbonaceous species, i.e., organic carbon (OC) and elemental carbon (EC), and water-soluble inorganic ions, e.g., SO_4^{2-}, NO_3^- and NH_4^+ are the major components of ambient aerosols (Liang et al., 2017; Du et al., 2014; Zheng et al., 2015; Tan et al., 2016). Biomass burning emissions constitute a large source of ambient particulate pollution, especially for carbonaceous components, i.e., primary organic carbon (POC) and black carbon (BC) on global scale (Bond et al., 2004; Tang et al., 2018; Salma et al., 2017; Titos et al., 2017). As an important aerosol component, black carbon from industrial and combustion emissions contributes to the enhanced $PM_{2.5}$ mass concentrations and influences regional radiative forcing (Chen et al., 2017). Fresh biomass burning aerosol was found to be mainly comprised of carbonaceous species which typically constitutes 50-60% of the total particle mass (Hallquist et al., 2009). Yao et al. (2016) identified approximately half of carbonaceous aerosols being contributed by biomass burning at Yucheng, a rural site in the North China Plain.

Biomass burning emissions also represent a potentially large source of secondary organic aerosol (SOA). The precursors and formation pathways of SOA from biomass burning emissions were investigated by extensive field observations (e.g., Zhu et al., 2015; 2016; 2017; Adler et al., 2011; Zhang et al., 2010; 2015). Based on morphological particle analysis, Yao et al. (2016) investigated the smoke emitted from biomass burning impacting SOA production. Sun et al. (2010) found that phenolic compounds, which were emitted in large amounts from wood combustion, can form SOA at high yields in aqueous-phase reactions. In addition, smoke from biomass burning can be transported thousands of kilometers downwind from the source areas. Biomass burning aerosol from Southeast Asia can be transported to China, Singapore and even further to North America (Liang et al., 2017; Hertwig et al., 2015; Peltier et al., 2008). Based on molecular tracer measurements, synoptic data as well as air mass back trajectory analysis, a fire episode was

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captured at a background site of East China with smoke advected from Southeast Asia (Liang et al., 2017).

The North China Plain (NCP) is one of the most polluted regions in China. Severe haze–fog of longer duration and more extensive coverage has occurred frequently in the NCP area, especially during the seasons of autumn and winter. NCP covers one quarter of China's cultivated land and yields 35% of the agricultural products in China (Boreddy et al., 2017). The rural population in NCP is also large and dense, and biomass burning activities are common in this region in form of cooking and heating. Intense fire activity typically occurs in October after the corn harvest. Abundant smoke is emitted from agricultural burning, i.e., residential biofuel combustion, open field burns, etc. Various field observations have investigated different aspects of biomass burning, e.g., seasonal variations, chemical and physical properties of smoke particles, spatial distribution, sources, transport, etc., in the NCP region (Cheng et al., 2013; Shen et al., 2018; Sun et al., 2013; 2016; Boreddy et al., 2017; Yan et al., 2015). However, these field investigations of the contribution of biomass burning to ambient aerosols in the NCP region were concentrated on the city of Beijing (Cheng et al., 2013; Zheng et al., 2015; Duan et al., 2004). Little field research about biomass burning was reported for rural areas in the NCP. In fact, biomass burning activities are common in the rural areas of the NCP region, and the resulting smoke aerosol can be transported to urban areas, e.g., the city of Beijing, resulting in haze episodic events. Meanwhile, biomass burning studies at rural sites can provide valuable source information of the biomass burning pollution in the North China region.

The objective of this study is to gain insights about the abundance of smoke during the typical biomass burning season, i.e., autumn-winter transition season, following the corn harvest. In this paper, we focus on quantifying multiple biomass burning tracers, i.e., LG, MN and K^+ as well as other chemical species in $PM_{2.5}$ in Gucheng (GC) during the typical biomass burning season. The results of this study demonstrated the biomass burning pollution status in the rural atmosphere of North China, as well as chemical properties of ambient aerosols under different biomass burning pollution levels.

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2. Site description and experimental Methods

2.1 Site description and sampling

Samples were collected at a rural site, Gucheng (GC, 39°09'N, 115°44'E; 15.2 m a.s.l), located on a platform at the China Meteorological Administration farm in the town of Gucheng (GC site), approximately 110 km southwest of Beijing and 35 km north of the city of Baoding (population of about 5 million) in Hebei province, as shown in ***Figure S1***. The station is surrounded by agricultural fields, with major crop species being corn and wheat. The dominant wind direction at GC is southwest and northeast during the study period. This site is upwind of Beijing, when the wind blows from the south or southwest, where heavily polluted cities and regions of Hebei province, i.e., Baoding, Shijiazhuang, Xingtai, Handan, are located. Thus, it is an appropriate station for representing the air pollution situation in the NCP region (Sheng et al., 2018; Chi et al., 2018; Xu et al., 2019; Kuang et al., 2020).

Daytime and nighttime $PM_{2.5}$ samples were collected from 15 October, 2016 to 23 November, 2016, by using $PM_{2.5}$ High-volume (Hi-Vol) samplers (GUV-15HBL1, Thermo Fisher Scientific CO., LTD), at the nominal flow rate of 1.13 m^3 min^{-1}. The daytime samples were collected from 07:00 to 19:00, while nighttime samples were collected from 19:00 to 07:00 local time of the next day. All $PM_{2.5}$ samples were collected on quartz fiber filters, prebaked at 850 °C for at least 5 h to remove carbonaceous material. A total of 33 couples of daytime/nighttime samples and 6 whole-day samples as well as 4 field blank samples were collected during the sampling period. The filters were stored at -20 °C after sample collection.

2.2 Experimental Methods

2.2.1 Anhydrosugar and water-soluble inorganic ion analysis

The quartz filter samples were analyzed for biomass burning anhydrosugar tracers, i.e., LG and MN, using an improved high-performance anion-exchange chromatography (HPAEC) method with pulsed amperometric detection (PAD) on a Dionex ICS-5000+ system. LG and MN were separated by a Dionex Carbopac MA1 analytical column and guard column with an aqueous sodium hydroxide (NaOH, 480 mM) eluent at a flow rate of 0.4 mL min^{-1}. The detection limit of LG and MN was 0.002 mg L^{-1} and 0.005 mg L^{-1}, respectively. More details about the

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HPAEC-PAD method can be found elsewhere (Iinuma et al., 2009).

The quartz filter samples were also analyzed for water-soluble inorganic ions by a Dionex ICS-5000+ ion chromatograph, including three anions (i.e., SO_4^{2-}, NO_3^-, Cl^-,) and five cations (i.e., NH_4^+, Ca^{2+}, Na^+, K^+ and Mg^{2+}). The cations were separated on an Ionpac CS12 analytical column and CG12 guard column with a 20 mM methanesulfouic acid as eluent at a flow rate of 1.0 mL min^{-1}, while the anions were separated on an Ionpac AS11-HC column and AG11-HC guard column with 21.5 mM KOH eluent at a flow rate of 1.0 mL min^{-1}. The water-soluble inorganic ion data were corrected by field blanks.

2.2.2 Organic carbon/elemental carbon analysis

OC and EC were measured on a punch (0.526 cm^2) of each quartz sample by a thermal/optical carbon analyzer (DRI Model 2001, Desert Research Institute, USA), using the Interagency Monitoring of Protected Visual Environments (IMPROVE) thermal evolution protocol with reflectance charring correction. The analytical error of OC was within 10%, and one sample of every 10 samples was selected at random for duplicate analysis. The detection limit of OC was 0.82 μgC cm^{-2} (Liang et al., 2017).

2.2.3 Gas online monitoring (i.e., NO, NO_2, SO_2, O_3, CO and NH_3)

During this campaign, commercial instruments from Thermo Fisher Scientific Co., LTD were used to measure O_3 (TE 49C), NO/NO_2/NOx (Model 42CTL), CO (TE 48CTL), and SO_2 (TE43CTL), while NH_3 was measured by an ammonia analyzer (DLT-100, Los Gatos Research, USA) at GC station. All measurement data quality was controlled according to standard gases (Xu et al., 2019; Lin et al., 2011; Meng et al., 2018; Ge et al., 2018).

2.2.4 Meteorological parameters

The meteorological parameters, including air temperature, relative humidity (RH) and wind speed at a 24-h resolution at the GC site are presented in Figure 1. During this campaign, the daily average RH value was observed at 77 ± 13%, with a range from 48% to 99%, while the daily wind speed was observed with an average value of 1.07 ± 1.14 m s^{-1}, exhibiting moist and stable synoptic conditions at this rural site during the autumn-winter transition season. During the sampling time from 15 October, 2016 to 23 November, 2016, the mean RH at GC was observed at 77%, exhibiting moist conditions. These meteorological parameters indicate that GC was

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characterized by humid and stagnant air masses. Moreover, there was rare precipitation during the sampling period at the GC site, except for two days, i.e., 20 and 27 October, 2016 (Figure 1).

2.2.5 Back trajectory and fire spot analysis

To characterize the transport pathways of the aerosol at the Gucheng site, back-trajectories were calculated with the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model via NOAA ARL READY Website (http://ready.arl.noaa.gov/HYSPLIT.php).

To investigate the influence of biomass burning activities in surrounding areas, fire hot spot counts were obtained from the Fire Information for Resource Management System (FIRMS) (available at https://firms.modaps.eosdis.nasa.gov/download/).

3. Results and discussion

3.1 Characteristics of chemical components in $PM_{2.5}$

In this study, the mass concentration of $PM_{2.5\text{-cal}}$ was reconstituted by the sum of carbonaceous components (1.6×OC + EC) and inorganic ions (SO_4^{2-} + NH_4^+ + NO_3^- + Cl^- + Ca^{2+} + Na^+ + K^+ + Mg^{2+}). Figure 1 describes the time-series variation obtained for daily $PM_{2.5\text{-cal}}$, and its major components (OC, EC, SO_4^{2-}, NO_3^- and NH_4^+), biomass burning tracers (LG, MN and K^+) and meteorological factors (temperature (T), relative humidity (RH), wind speed (WS) and rainfall) during the sampling period. The average daily $PM_{2.5\text{-cal}}$ mass concentration in the autumn-winter transition season at GC reached 137 ± 72.4 μg m^{-3}, ranging from 23.3 μg m^{-3} to 319 μg m^{-3} (Table 1), which is higher than during the severe winter haze in January, 2013 at an urban site in Beijing (121.0 μg m^{-3}) (Zheng et al., 2015). The mass concentrations of these chemical species during the day are distributed as follows (from highest to lowest): OC > EC > NO_3^- > SO_4^{2-} > NH_4^+ > Cl^- > Ca^{2+} > K^+ > Na^+ > Mg^{2+}. Organic matter (OM) was the most abundant component, the daily average value of which was 70.4 ± 49.6 μg m^{-3}, accounting for nearly half (46.7%) of $PM_{2.5\text{-cal}}$ mass, indicating obvious organic pollution at the rural site in the North China Plain during the sampling season.

The measured daily average concentrations of biomass burning tracers, i.e., LG, MN and K^+ in $PM_{2.5}$ during our study were 0.79 ± 0.75 μg m^{-3}, 0.03 ± 0.03 μg m^{-3} and 1.52 ± 0.62 μg m^{-3} (Table 1). The anhydrosugar levels (LG and MN) in this study were both higher than those

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observed in the city of Beijing during summer and winter seasons (Cheng et al., 2013; Yan et al., 2015). The highest concentrations of LG in GC were observed on 31 October, 2016 with 4.37 μg m^{-3}, which is a sharp increase (over 30 times) of the minimum concentration (0.14 μg m^{-3}) during that period. Accordingly, the $PM_{2.5\text{-cal}}$ concentration during that period was also elevated (as high as 236 μg m^{-3}) (Figure 1). Secondary inorganic aerosol (sulfate, SO_4^{2-}; nitrate, NO_3^- and ammonium, NH_4^+, SNA) species, were the major water soluble ions, accounting for 82.8% of total water soluble ions, the daily average values of which were 10.5 ± 6.87 μg m^{-3}, 15.9 ± 9.29 μg m^{-3} and 10.9 ± 5.51 μg m^{-3} (Table 1). SNA species exhibited a synchronous temporal trend, while the NO_3^- concentrations exceeded those of SO_4^{2-} at the GC site, in contrast to the results of previous studies, e.g., Tan et al. (2016), who found SO_4^{2-} to be the dominant species in $PM_{2.5}$ during winter time in 2006 in Beijing. Similarly, Chi et al., (2018) also found NO_3^- concentrations exceeded those of SO_4^{2-} at both Beijing and GC sites during the winter time in 2016, although they observed that NH_4^+ was the dominant component of SNA (the concentrations of SO_4^{2-}, NO_3^- and NH_4^+ were 14.0 μg m^{-3}, 14.2 μg m^{-3}, and 24.2 μg m^{-3}, respectively).

3.2 Day-night variations in the characteristics of $PM_{2.5}$ chemical components

Carbonaceous components and biomass burning tracers exhibited higher levels during nighttime than daytime, while secondary inorganic ions showed the opposite pattern, i.e., higher concentrations during daytime than nighttime (Figure 2 and Figure S2). Besides, the gap of carbonaceous components and anhydrosugars between daytime and nighttime (two-fold) was more significant than for secondary inorganic ions. Elemental carbon and primary organic components are not subject to significant differences in chemical reactions in ambient air between daytime and nighttime, and they will be mainly influenced by the variations of the planetary boundary layer (PBL) height. In the night, the PBL height decreases, compressing air pollutants into a shallow layer, and subsequently resulting in faster accumulation and higher concentrations of pollutants (Zheng et al., 2015; Zhong et al., 2018; 2019). The contributions of OM and EC to $PM_{2.5\text{-cal}}$ were observed to be higher at nighttime (53.9% and 16.6%) than daytime (43.8% and 13.7%) as well (Figure 3). Moreover, the chemical degradation of LG may occur due to photochemical reaction in the ambient aerosols, further lowering the LG levels in daytime (Sang et al., 2016; Gensch et al., 2018). Correspondingly, the contribution of LG to $PM_{2.5\text{-cal}}$ during

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nighttime (0.64%) was observed to be higher than that during daytime (0.37%) (Figure 3). However, secondary inorganic ions have an important formation pathway, i.e., photochemical processing, during daytime. Thus, the secondary inorganic species (SO_4^{2-}, NO_3^- and NH_4^+) were enhanced during daytime due to photochemical formation. Moreover, such an enhancement in secondary transformations during daytime is more evident in terms of the mass contributions of secondary inorganic ions to $PM_{2.5\text{-cal}}$, that the contributions of SO_4^{2-}, NO_3^- and NH_4^+ to $PM_{2.5\text{-cal}}$ decreased from daytime (9.9%, 14.5% and 10.0%) to nighttime (6.5%, 9.6% and 7.1%) (Figure 3).

In addition, the concentrations of other water-soluble inorganic ions, i.e., K^+ and Cl^- during nighttime (1.78 ± 0.95 μg m^{-3} and 6.08 ± 4.00 μg m^{-3}) were higher than those in daytime (1.43 ± 0.54 μg m^{-3} and 4.33 ± 2.30 μg m^{-3}), while their contributions to $PM_{2.5\text{-cal}}$ were reversed, due to the significant accumulation and higher concentrations of pollutants during nighttime. As Ca^{2+}, Mg^{2+} and Na^+, mainly emitted from primary natural sources, such as dust, soil resuspension and sea salt, are subject to more activity during the daytime and also influenced by the airflow dynamics, the contribution of those species in nighttime were lower than those during daytime, especially for Ca^{2+}, decreasing from 2.2% in daytime to 0.9% at nighttime (Figure 3).

3.3 Biomass burning episodes and the impacts on chemical $PM_{2.5}$ characteristics

An episode with high biomass burning tracer levels was encountered on 31 October, 2016. The concentrations of LG in $PM_{2.5}$ during this one-day episode (4.37 μg m^{-3}) were significantly higher than those during typical transition season at the GC site (0.69 ± 0.47 μg m^{-3}) (Figure 1). Here, we mainly distinguish four sub-periods based on daily LG concentrations during the time frame from 15 October to 23 November, 2016. The four periods were separated as follows: 15-30 October (Period I: Minor biomass burning), 31 October (Period II: Intensive biomass burning), 1-14 November (Period III: Major biomass burning), 15-23 November (Period IV: Heating season). Table 2 compares the concentrations of $PM_{2.5\text{-cal}}$ mass, chemical components and gases at the GC site during these four periods, as well as the ratios between the intensive, major BB periods and heating season to minor BB period. The level of LG during the intensive BB episode II was about 12 times of that during the minor BB period I. K^+ and Cl^-, the common biomass burning tracers utilized in many studies (Duan et al., 2004; Cheng et al., 2013), were also observed with increased abundance during intensive BB episode II. When entering into November,

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the weather was becoming cold, and thus combustion activities for heating in the rural areas commenced, resulting in the ambient levels of LG to strongly increase to 0.92 ± 0.47 μg m^{-3} during period III, about 3 times of those in Period I. The central heating systems in North China cities were operated during period IV, and the ambient level of LG was observed at 0.96 ± 0.63 μg m^{-3}, which was slightly higher than that in period III.

The concentrations of OC and EC were also observed strongly increased in period II (Table 2), especially for OC, increased to 59.9 ± 25.3 μg m^{-3} during the intensive BB episode II, nearly 6 times of that during the minor BB period (16.2 ± 7.52 μg m^{-3}). Accordingly, the LG/OC ratio increased to 0.045 during period II, which is higher than most of the published field observations, i.e., at urban sites (Zhang et al., 2008; Cheng et al., 2013; Zhang et al., 2014), rural sites (Sang et al., 2013; Ho et al., 2014; Pietrogrande et al., 2015; Mkoma et al., 2013) and agricultural sites (Ho et al., 2014; Jung et al., 2014), yet lower than at an urban site in northern Italy during winter time (Pietrogrande et al., 2015). During the major BB (period III) and heating season (period IV), due to the combustion of coal and biofuel for heating, OC remained at a high level (55.2 ± 17.1 μgC m^{-3} and 69.4 ± 24.6 μgC m^{-3}, respectively). These levels are more than 3 times of that during the minor BB period I. Due to the abundance of organic aerosols, the LG/OC ratios during periods III and IV decreased to 0.016 ± 0.005 and 0.014 ± 0.006, respectively, even lower than those in the minor BB period I (0.025 ± 0.008).

Compared to the carbonaceous components, the concentrations of secondary inorganic aerosol species (SO_4^{2-}, NO_3^-, NH_4^+) exhibited a different pattern, i.e., showing no obvious differences between minor BB period I and other three periods. The ratios of SO_4^{2-}, NO_3^-, NH_4^+ during periods II, III and IV to period I were all around 1.0 (Table 2), with no increasing trend. Moreover, the relationships between LG and OC (and EC) were better than those between LG and SNA during daytime and nighttime ***(Figure S3).*** The precursor gases of SNA, i.e., SO_2, NO, NO_2 and NH_3, were observed to have an increasing trend when biomass burning was prevalent during periods III and IV, with the ratios to period I arranged from 1.13 to 1.90 (Table 2). The time-series variations of the gases (SO_2, NO_x, NH_3, CO and O_3) and PBL during the sampling period are shown in ***Figure S4.*** The primary emission gases were exhibited negative relationships with PBL, while O_3 exhibited obvious positive relationship with PBL (***Figure S5***). Combustion from

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different fossil fuels (coal, gasoline, diesel, etc.) and biomasses (straws, woods, leaves, etc.) can all emit CO into the atmosphere (Streets et al., 2003; Chantara et al., 2019; Merico et al., 2020). Due to the more abundant combustion in the colder weather, the concentrations of CO also increased to 1.65 ± 0.53 ppm and 1.18 ± 0.83 ppm during the major biomass burning period III and the heating season period IV, respectively.

The combustion of biomass, especially of agricultural residues (e.g., wheat and corn straw) is very common in the rural areas in North China during the autumn-winter transition period. During the autumn harvest season in North China, wheat and corn straw burning is common practice, resulting in more abundant fire spots when entering into November than period I (Figure 4). The intense biomass burning event on 31 October, 2016 was also supported by air mass back trajectory analysis (Figure 5), performed with the TrajStat software. Based on the 48 h back trajectories at the GC site at 00:00 (UTC time) on 1 November, 2016, the air mass at the GC site was restricted in the region of Bejing-Tianjing-Hebei, the polluted area where fire spots were numerous. However, on the previous and following day of this episode, i.e., 31 October and 2 November onward, the air masses arriving at GC were advected from the northwest of Mongolia, where mostly desert areas are present, with less farm land and rare biomass burning activities (Figure 5).

Mean percentiles of major components in $PM_{2.5}$ with respect to different BB pollution periods at GC site during the sampling time are shown in Figure 6. With the variation of BB pollution periods, the EC fraction seems to exhibit no obvious change during periods I, II and III, but slightly increased during the heating season (period IV), while the OC fraction increased significantly. The contributions of sulfate, nitrate and ammonium to $PM_{2.5\text{-cal}}$ all decreased sharply from the minor BB period to the intense period (Figure 6). This suggests that organic aerosol species become more important during BB pollution periods, concerning their contribution to the $PM_{2.5\text{-cal}}$, while EC has no such character. The OM percentage during intense BB period II was 65.4%, about double of that during the minor biomass burning period (34.0%), indicating that there was a large fraction of OM in $PM_{2.5\text{-cal}}$ originating from BB at the GC site during intensive BB period II. Opposite to OM, contributions of secondary inorganic ions to $PM_{2.5\text{-cal}}$ significantly decreased with the BB pollution becoming more severe. The contributions of SO_4^{2-}, NO_3^- and NH_4^+ to $PM_{2.5\text{-cal}}$ during the minor BB episode (11.6%, 20.5% and 12.5%) obviously declined

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during the intense BB episode (1.73%, 7.73% and 4.24%).

3.4 Relationships among tracers during different biomass burning pollution periods

In addition to pollution level information of biomass burning molecular tracers, the ratios between them could also be used to identify the different biomass types or indicate the burning formation processes of atmospheric aerosols. The LG/MN ratios during minor, intense, major biomass pollution and heating season periods were observed at high values, i.e., 24.9, 24.1, 24.8 and 18.3 respectively (Table 2, Figure 7). LG and MN in the four periods showed a good relationship (Figure 7a, $R^2 = 0.94$). Based on source emission studies, the LG/MN ratios from crop residue burning, i.e., rice straw, wheat straw, and other straws, were similar and characterized by high values, yet overlapped with those from hard wood and leaf burning (>10.0), while soft wood characterized by relatively lower LG/MN ratios (< 5.0) (Cheng et al., 2013). According to the local habits, woods are also commonly used as biofuels for stove heating in North China, since they allow long-time heating duration. The influence of wood combustion for heating becoming non-negligible during the cold season caused the LG/MN ratios during the intense BB episode (Period II) and typical heating season (Period IV) to slightly decrease.

The concentrations of LG and K^+ during minor, major BB episode and heating season were correlated well (Figure 7b, $R^2 = 0.70$), while the red dot of period II being off from the fitted regression line. The LG/K^+ ratios during III and IV (0.52 and 0.53) were similar to those during a BB episode at an urban site of Beijing during winter time (LG/K^+ = 0.51) (Cheng et al., 2013). However, the LG/K^+ ratio during the intense BB period II increased to 1.67, which was significantly higher than that in typical straw combustion (< 1.0). Correspondingly, there was a significant drop in temperatures at the GC site during period II, with the average daily temperature sharply decreasing from 7.5 °C on 30 Oct to 0.31 °C on 31 Oct, 2016, while the average temperature at night of 31 Oct decreased to -3.4 °C (Figure 1). Hence, the combustion activities were apparently intense around the sampling site for heating purposes. Compared to K^+, there is a large enrichment of LG in wood burning emissions, based on the results from previous biomass source combustion studies (Engling et al., 2006; Chantara et al., 2019). The influence of softwood

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and/or other materials from softwood, which are commonly used as biofuels for stove heating in North China (Sang et al., 2012; Cheng et al., 2013; Zhou et al., 2017), should be larger during this low temperature period. Moreover, LG/K^+ ratios also can be influenced by combustion conditions, i.e., smoldering versus flaming burns. Biofuels are typically subject to smoldering combustion condition in residential stoves for heating purposes in the rural areas in North China, which was reflected in relatively higher LG/K^+ ratios than during flaming combustion (Schkolnik et al., 2005; Lee et al., 2010).

4. Summary and conclusion

Anhydrosugars, including levoglucosan and mannosan, and water-soluble potassium ion were employed as molecular tracers to investigate the characteristics of biomass burning activities as well as chemical properties of ambient aerosols under different biomass burning pollution levels. The measured daily average concentrations of LG, MN and K^+ in $PM_{2.5}$ during a typical biomass burning season, from 15 October to 30 November, 2016 were 0.79 ± 0.75 μg m^{-3}, 0.03 ± 0.03 μg m^{-3} and 1.52 ± 0.62 μg m^{-3}. The concentrations of carbonaceous components and biomass burning tracers were observed higher at nighttime than daytime, while the patterns of secondary inorganic ions (SO_4^{2-}, NO_3^- and NH_4^+) were opposite, since they were enhanced by photochemical formation during daytime. An episode with extreme biomass burning tracer levels was encountered on 31 October, 2016, with concentrations of LG as high as 4.37 μg m^{-3}. Comparing the chemical composition between different biomass burning periods, it was apparent that biomass burning can considerably elevate the levels of organic components, while not showing a significant effect on the production of secondary inorganic ions, although their precursors were observed at increased levels. Moreover, due to more local soft wood and smoldering combustion taking place for heating under the low temperatures, the LG/K^+ ratio during the intensive BB period was abnormally higher than those in other BB periods.

Data availability. The data used in this study can be obtained from this open link: https://pan.baidu.com/s/11bKUZff1KJbzNVxS3VsLaA code: jvqx. It is also available from the corresponding author upon request (lianglinlin@cma.gov.cn).

Author contributions. LL designed conducted all observations and drafted the paper. GE revised

the paper and improved the English writing. XL drew the Figure 4 and Figure 5. CL, WX, YC, ZD, GZ, JS and XZ interpreted the data and discussed the results. All authors approved the final version for publication.

Competing interests. The authors declare that they have no conflict of interest.

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Table 1. Average concentrations and the range of $PM_{2.5\text{-cal}}$ and its chemical components, biomass burning tracers (μg m^{-3}), gaseous species, ratios of OC/EC and LG/OC, as well as meteorological data observed at GC site at daytime, nighttime and whole day, respectively, during the sampling period from 15 Oct to 23 Nov 2016.

Species	Daytime (N = 34)		Nighttime (N = 33)		Whole period (N = 37)	
	Concentration	Range	Concentration	Range	Concentration	Range
$PM_{2.5\text{-cal}}$	117 ± 58.8	19.0 - 225	170 ± 116	21.1 - 465	137 ± 72.4	23.3 - 319
OC	26.8 ± 15.7	3.78 - 64.8	61.6 ± 49.5	2.88 - 175	44.0 ± 31.0	4.13 - 117
EC	13.4 ± 8.49	1.44 - 34.0	30.9 ± 28.5	2.21 - 129	21.7 ± 15.8	2.46 - 74.9
TC	49.3 ± 27.6	5.76 - 124	92.5 ± 73.6	5.10 - 289	65.8 ± 44.1	7.36 - 192
OC/EC	2.02 ± 1.26	1.09 - 3.31	2.25 ± 1.04	1.04 - 6.72	1.95 ± 0.60	0.83 - 3.10
SO_4^{2-}	12.1 ± 9.31	1.65 - 39.7	9.02 ± 6.22	1.55 - 23.2	10.5 ± 6.87	1.66 - 29.5
NO_3^-	16.9 ± 9.96	1.85 - 41.2	13.1 ± 8.52	1.56 - 38.0	15.9 ± 9.29	2.40 - 45.2
Cl^-	4.33 ± 2.30	0.82 - 9.46	6.08 ± 4.00	0.62 – 16.0	4.90 ± 2.46	0.93 - 9.37
NH_4^+	11.7 ± 6.76	1.84 - 26.0	10.0 ± 5.75	1.33 - 22.2	10.9 ± 5.51	1.99 - 25.4
K^+	1.43 ± 0.54	0.20 - 2.64	1.78 ± 0.95	0.22 - 4.19	1.52 ± 0.62	0.50 - 2.96
Mg^{2+}	0.26 ± 0.14	0.07-0.64	0.19 ± 0.09	0.06 - 0.38	0.14 ± 0.12	0.04 - 0.43
Ca^{2+}	2.24 ± 1.01	1.02-4.75	1.56 ± 0.08	0.77 - 3.56	1.54 ± 0.90	0.49 - 3.84
Na^+	0.44 ± 0.17	0.10 - 0.79	0.43 ± 0.24	0.10 - 1.31	0.42 ± 0.17	0.11 - 0.88
NO_3^- / SO_4^{2-}	1.67 ± 0.82	0.75 - 5.52	1.54 ± 0.57	0.74 - 3.50	1.65 ± 0.62	0.78 ± 3.96
Levoglucosan	0.57 ± 0.62	0.05 - 3.74	1.10 ± 0.99	0.05 - 4.82	0.79 ± 0.75	0.14 - 4.37
Mannosan	0.024 ± 0.023	0.00 - 0.14	0.05 ± 0.04	0.00 - 0.21	0.03 ± 0.03	0.00 - 0.18
LG/OC	0.018 ± 0.011	0.005 - 0.067	0.020 ± 0.010	0.004 - 0.047	0.020 ± 0.009	0.006 - 0.045
NO (ppb)	23.0 ± 14.7	2.07 - 56.0	45.9 ± 29.5	1.59 - 96.9	31.8 ± 18.3	1.81 - 68.5
NO_2 (ppb)	25.8 ± 10.4	8.18 - 51.6	29.3 ± 9.37	8.81 - 51.1	26.6 ± 8.74	8.62 - 51.4
SO_2 (ppb)	9.78 ± 4.96	3.11 - 22.5	9.63 ± 5.67	2.91 - 28.7	8.61 ± 4.04	3.37 - 20.4
CO (ppm)	0.96 ± 0.73	0.03 - 2.49	1.29 ± 1.04	0.02 - 3.26	1.05 ± 0.76	0.12 - 2.48
O_3 (ppb)	13.0 ± 9.10	1.42 - 41.84	5.00 ± 5.73	1.60 - 24.30	9.25 ± 5.78	1.67 - 24.0
NH_3 (ppb)	16.4 ± 11.3	1.68 - 46.2	18.3 ± 10.7	1.03 - 42.7	17.1 ± 9.88	1.46 - 44.4
Temperature (°C)	7.71 ± 4.01	- 2.07-15.9	3.30 ± 4.69	- 6.60 - 14.5	6.95 ± 4.58	- 4.33 - 15.4
Relative Humidity (%)	68 ± 17	31 - 98	85 ± 14	34 - 100	77 ± 13	48 - 99
Wind speed (m s^{-1})	1.43 ± 1.17	0.09 - 5.65	0.79 ± 1.55	0.03 - 7.19	1.07 ± 1.14	0.04 - 5.02

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Table 2. Concentrations of chemical components in $PM_{2.5}$ aerosols as well as their ratios and gaseous species collected at the GC site, during the four biomass burning periods (i.e., Minor, Intensive, Major and Heating period) from 15 Oct to 23 Nov 2016.

Species	Period I (15-30 Oct) Minor BB	Period II (31 Oct) Intensive BB		Period III (1 -14, Nov) Major BB		Period IV (15 -23, Nov) Heating period	
	Concentration	Concentration	Ratio*	Concentration	Ratio*	Concentration	Ratio*
$PM_{2.5\text{-cal}}$	81.0 ± 44.5	235	2.91	163 ± 46.7	2.01	189 ± 83.0	2.33
Levoglucosan	0.36 ± 0.14	4.37	12.1	0.90 ± 0.37	2.50	0.96 ± 0.63	2.67
Mannosan	0.015 ± 0.005	0.18	12.0	0.038 ± 0.015	2.53	0.050 ± 0.026	3.33
OC	16.2 ± 7.52	96.3	5.93	55.2 ±17.1	3.41	69.4 ± 24.6	4.28
EC	12.2 ± 5.85	36.0	2.96	25.5 ± 10.1	2.09	36.4 ± 21.5	2.98
TC	28.4 ± 13.1	132	4.66	80.9 ± 34.6	2.85	106 ± 55.3	3.73
SO_4^{2-}	10.3 ± 8.96	4.56	0.44	11.8 ± 6.02	1.15	9.08 ± 3.87	0.88
NO_3^-	16.6 ± 12.9	18.1	1.09	16.5 ± 6.42	0.99	12.6 ± 5.76	0.76
NH_4^+	10.1 ± 7.40	10.0	0.99	12.0 ± 4.35	1.19	10.3 ± 3.62	1.02
K^+	1.16 ± 0.36	2.61	2.25	1.76 ± 0.46	1.52	1.65 ± 0.84	1.42
Cl^-	3.46 ± 1.97	7.49	2.16	5.58 ± 2.16	1.61	6.27 ± 2.58	1.81
OC/EC	1.53 ± 0.35	2.67	1.75	2.31 ± 0.59	1.51	2.04 ± 0.31	1.33
NO_3^-/ SO_4^{2-}	1.74 ± 0.60	3.96	2.28	1.50 ± 0.35	0.86	1.42 ± 0.47	0.82
LG/OC	0.025 ± 0.008	0.045	1.80	0.016 ± 0.005	0.64	0.014 ± 0.006	0.56
LG/EC	0.039 ± 0.019	0.121	3.10	0.038 ± 0.017	0.97	0.028 ± 0.013	0.72
LG/MN	24.9 ± 4.44	24.1	0.97	24.8 ± 6.46	1.00	18.3 ± 4.27	0.73
LG/K^+	0.36 ± 0.081	1.67	4.64	0.51 ± 0.16	1.42	0.53 ± 0.15	1.47
NO (ppb)	21.7 ± 12.5	21.7	1.00	39.6 ± 15.4	1.82	39.3 ± 23.6	1.81
NO_2 (ppb)	21.8 ± 4.95	26.5	1.22	32.7 ± 7.27	1.50	24.6 ± 10.2	1.13
NO_X (ppb)	43.6 ± 16.3	48.2	1.11	72.4 ± 17.8	1.66	64.0 ± 33.4	1.47
SO_2 (ppb)	5.83 ± 2.46	8.04	1.38	11.1 ± 4.10	1.90	9.75 ± 3.31	1.67
CO (ppm)	0.44 ± 0.33	0.70	1.59	1.65 ± 0.53	3.75	1.18 ± 0.83	2.68
O_3 (ppb)	9.79 ± 4.88	23.2	2.37	7.51 ± 3.87	0.77	9.59 ± 7.55	0.98
NH_3 (ppb)	14.3 ± 6.12	11.1	0.78	18.6 ± 8.03	1.30	21.2 ± 14.2	1.48

*: indicates that the ratios of the heating period, intense BB period or major biomass burning period were divided by those from the minor BB period.

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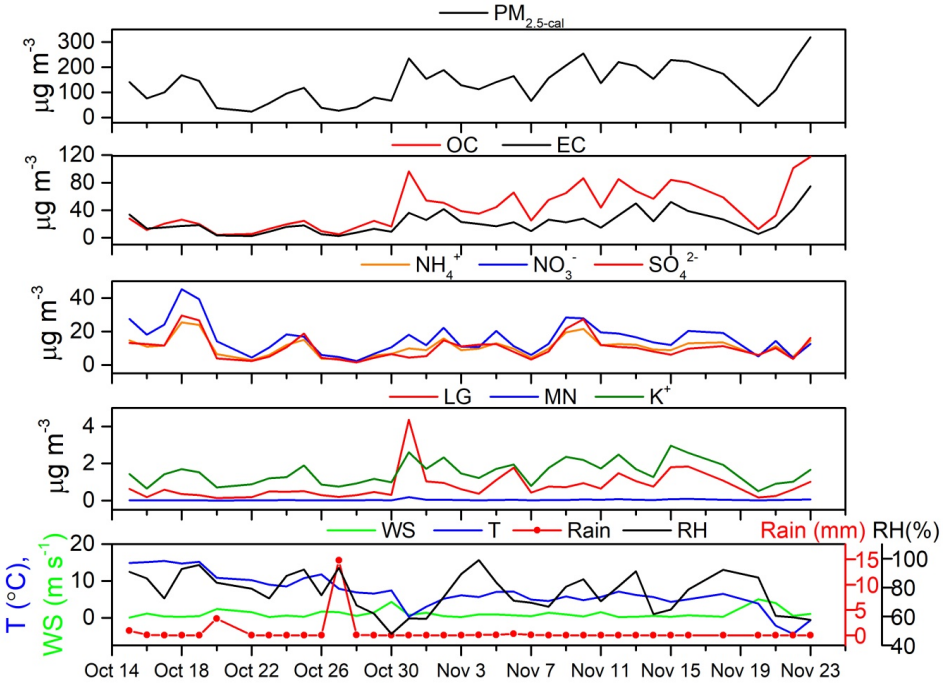

Figure 1. Time-series variation obtained for $PM_{2.5\text{-cal}}$ and its major components (OC, EC, SO_4^{2-}, NO_3^- and NH_4^+), biomass burning tracers (LG, MN and K^+) and meteorological factors (temperature (T), relative humidity (RH), wind speed (WS) and rainfall) at the GC site during the sampling period from 15 Oct to 23 Nov 2016.

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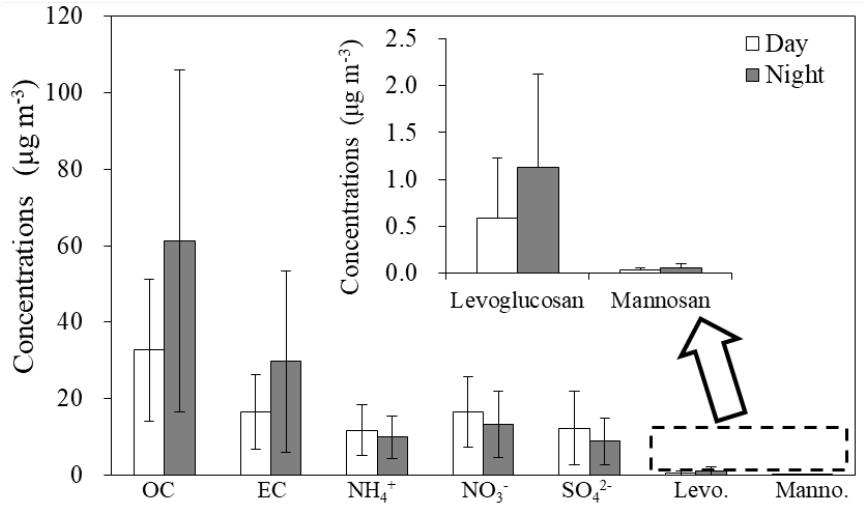

Figure 2. Day and night distributions of mean concentrations of main chemical components (OC, EC, SO_4^{2-}, NO_3^- and NH_4^+) and biomass burning tracers (LG and MN) in $PM_{2.5}$ observed at GC site during the sampling period.

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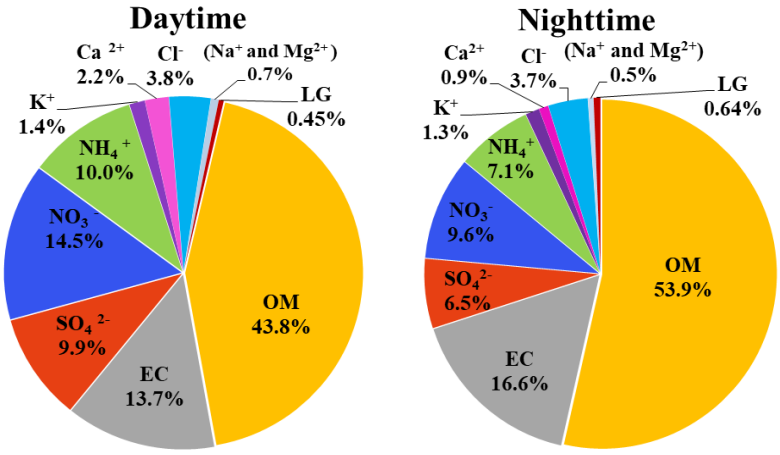

Figure 3. Percent contributions of individual component mass concentrations to total estimated $PM_{2.5\text{-cal}}$ mass in daytime and nighttime during the sampling period.

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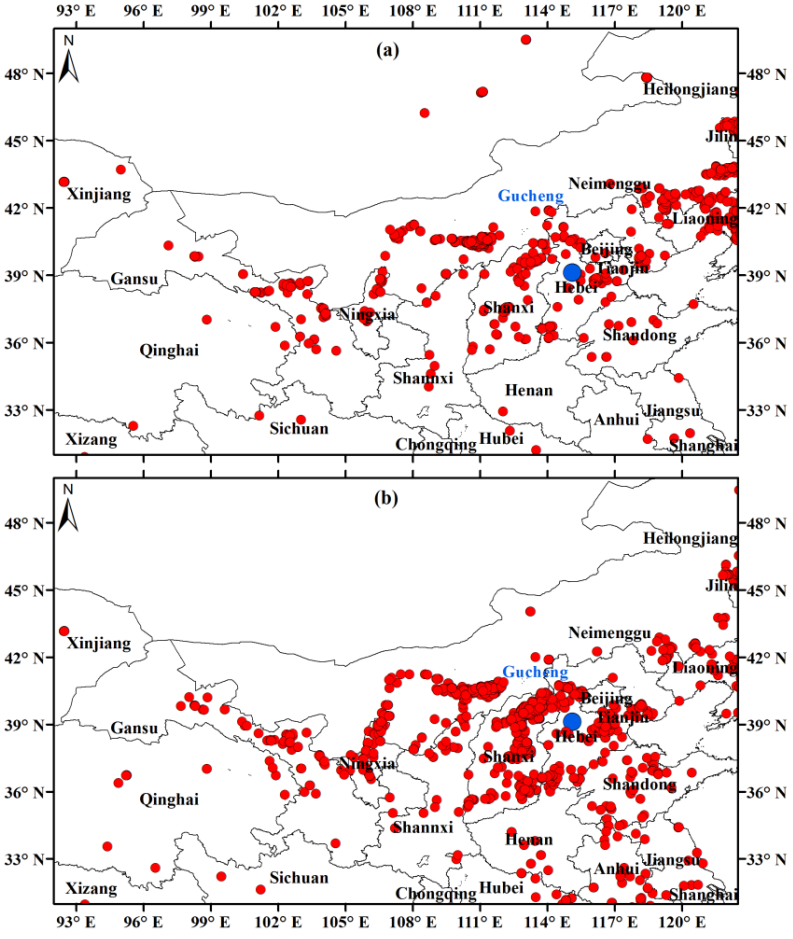

Figure 4. Fire spots at GC site and the surrounding provinces from (a) 15-30 October, 2016 and (b) 1 -23, November, 2016, observed by MODIS Terra satellites (blue dot is GC station).

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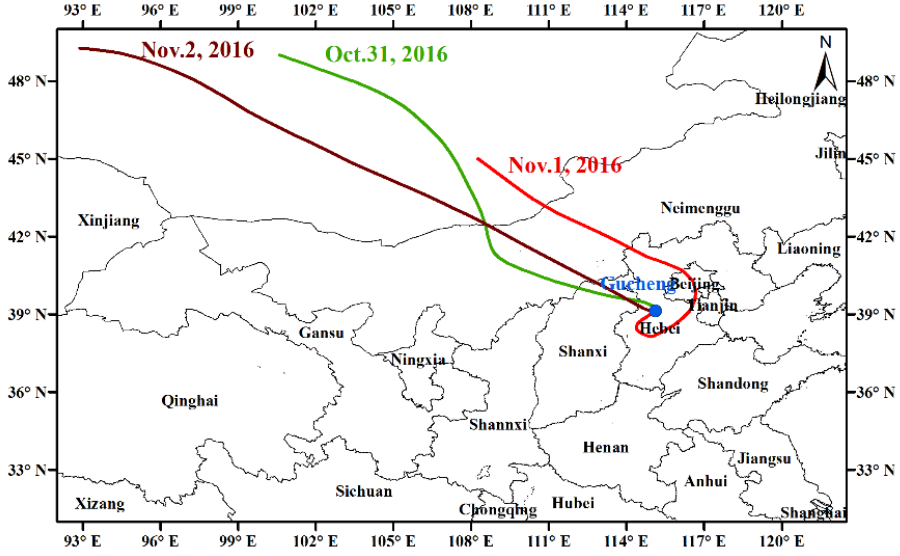

Figure 5. 48 h back trajectories at 500 m at GC site (39°09'N, 115°44'E) at 00:00 (UTC time) from 31 October to 2 November, 2016.

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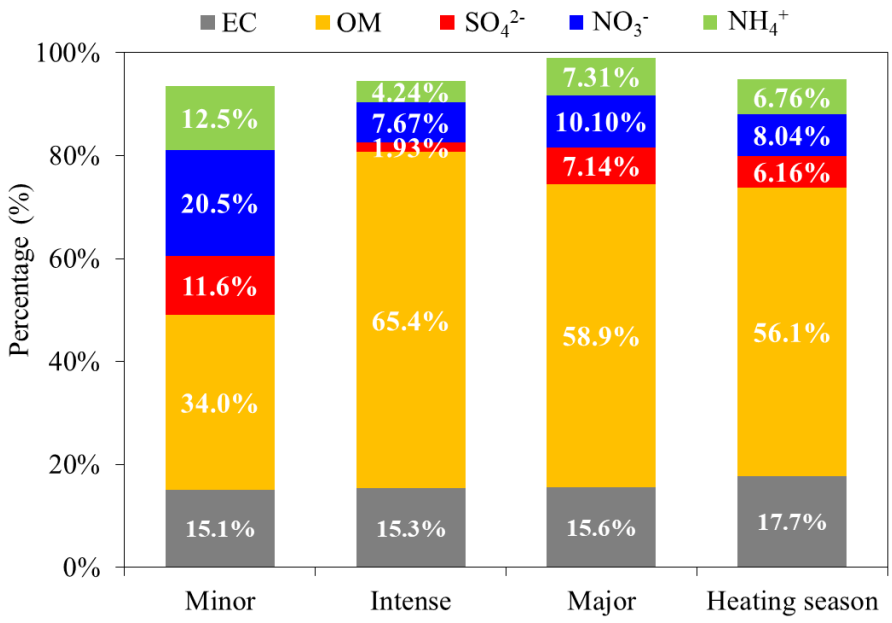

Figure 6. Mean percentiles of major components in $PM_{2.5}$ with respect to different biomass burning pollution periods at GC site during the sampling time.

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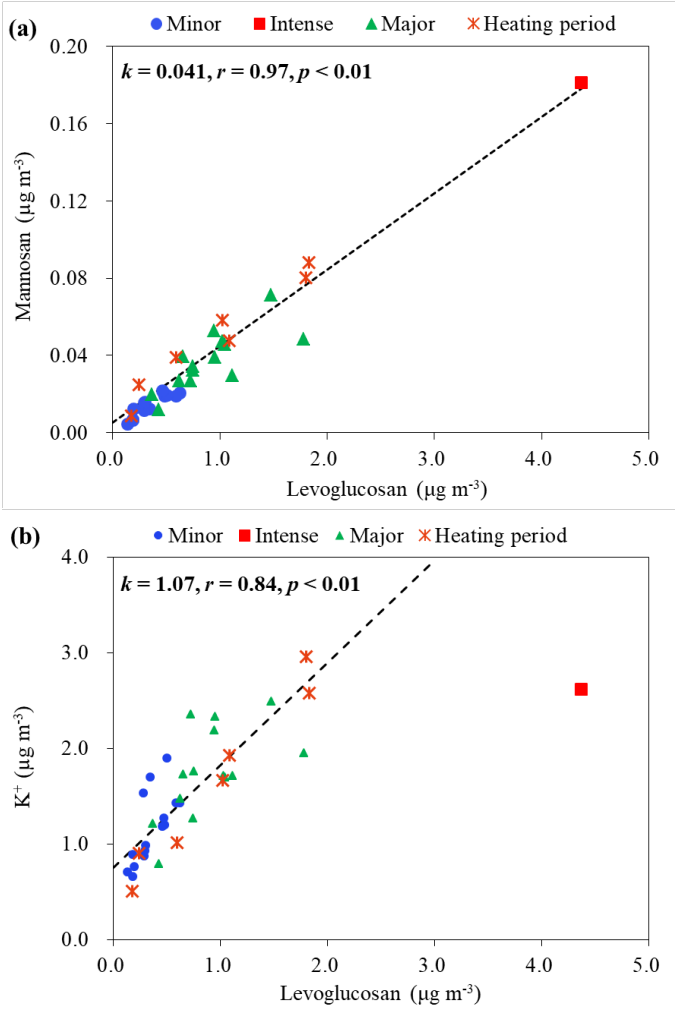

Figure 7. Scatter plots of (a) levoglucosan versus mannosan, (b) levoglucosan versus K^+.