Monitoring Air Quality in Urban Centres: New Insights from Douala, Cameroon

Air quality progressively deteriorates as urbanization, motorization and economic activities increase. Aerosol particles smaller than 2.5 µm (PM$_{2.5}$), a widespread form of pollution is an emergent threat to human health, the environment, quality of life, and the world’s climate. The composition of these particles is an important aspect of interest not only related to possible health and environmental effects of the elemental content but the elemental determination which also adds valuable information for source apportionment. This study investigates and evaluates the level of PM$_{2.5}$ in the town of Douala. Monitoring was conducted over a one month period at three locations; two sites in industrial zones and a residential zone. The particles were collected using a cyclone that separates the PM$_{2.5}$ from the air stream and impacts them on polycarbonate filters which were changed every 24-hour sampling period. The samples were analyzed for particulate mass concentration, black carbon (BC) and trace elements. Trace element analysis was done by EDXRF. Cl, K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, Br, Sr, and Pb were identified and quantified for samples. Local meteorology was used to study variations in PM$_{2.5}$ mass concentrations. Possible sources for the pollutants were also investigated. The mean particle mass concentration was 252 ± 130.8 µg/m$^3$ while BC attained a maximum of 6.993 µg/m$^3$. The influence of leaded gasoline was inferred while combustion and road traffic were identified as the major anthropogenic activities emitting particulate matter. Trends in meteorological parameters were influenced by thunderstorms. Sea spray was identified as another major contributor to aerosol PM in this city. The industrial zones had higher concentrations. This study highlights high pollution levels in the city of Douala, with potential important impacts on the health of the regional population.

Keywords: PM$_{2.5}$, Air Quality, Aerosol, Mass Concentration, EDXRF

Introduction

With the recent upsurge in globalization and industrialization coupled with increasing pressures of global climate change, deforestation and shifts in land use pattern, air pollution is emerging as one of the major factors influencing human health, agriculture and natural ecosystems (Agrawal et al., 2003; Kuan et al., 2017; Ana et al., 2018). Air quality is of particular concern due to the degradation of human health attributed to it. Air borne particles that play pivotal roles in human health and atmospheric processes such as fog and cloud formation, visibility, solar radiation and precipitation, acidification of clouds, rain and fog, and climate change as a whole are of particular interest (Goldoni et al., 2006; Dawson et al., 2007; Kawata et al., 2007; Donaldson et al., 2009; Kelly and Fussell, 2011; Tiwari et al., 2012; Amodio et al., 2013). Several epidemiological studies have indicated a strong association between high concentrations of inhalable particles and increased mortality and morbidity (Russell and Brunekreef, 2009; Bell et al., 2009; Kuan et al., 2017; Cao et al., 2018; Ariundelger et al.,...
especially in urban centers where urbanization, motorization, and rapid economic growth rapidly deteriorate the quality of the air (Boman et al., 2009). The size of particles affect their ability to penetrate the human respiratory system causing adverse health effects (Schwarze et al., 2006; Seinfeld and Pandis, 2006; Kaonga and Ebenso, 2011). Exposure to fine particles especially PM2.5 which are aerosol particles with aerodynamic diameter ≤ 2.5µm can cause short and long term effects such as decreased lung function, alterations in tissue and lung structure, increased respiratory symptoms, alterations in the respiratory tract and even premature death (Tsai et al., 2003; Katsouyanni et al., 2009; Samet et al., 2012; Kuan et al., 2017). Increased toxicity and PM carcinogenicity have been strongly associated with the elemental composition of PM and the presence of polycyclic aromatic hydrocarbons (PAHs) in the finer particles. According to Huggins (2004) and Linak (2000), some of these elements are essential to maintain metabolic activities in the human body. However, at higher concentrations, they can lead to poisoning. More attention is required for “Heavy metals”, usually referred to as metallic chemical elements having a relatively high density and toxic or poisonous at low concentrations (Hg, Cd, As, Cr, Ni and Pb). In addition, trace metals are proven to be useful tracers and are extensively used to identify sources of emissions to be targeted by the emission reduction policies (Gotschi et al., 2005; Querol et al., 2006; Querol et al. 2007; Viana et al. 2007; Jeong et al. 2008).

According to WHO (2005), Forster (2007) and Tai et al. (2012), climatic conditions have direct effects on the concentration, dispersion and life time of aerosol particles in the atmosphere. The dynamics of the atmosphere and the meteorological conditions play a vital role in governing the fate of air pollutants. Lecoeur et al. (2012) states that concentrations of PM are strongly dependent on meteorological conditions of which temperature, wind speed, humidity, rain rate and mixing height are the variables that impact PM concentrations the most. In this study, the relationship between ambient PM concentration and meteorological factors, such as temperature, rainfall, wind speed and direction and relative humidity is statistically analyzed.

In Cameroon, Douala is of particular interest for air pollution studies because of its dense population coupled with intense industrial and commercial activities (Tchotsoua, 2007; Kemajou et al., 2007). However, there has been limited air pollution research in this city.

With focus on PM2.5, spatial analysis and temporal variations of air pollution in areas of different development typology in Douala, the economic capital of Cameroon was studied. Detailed measurements of air pollution (PM2.5) were carried out at street sites in 2 industrial zones (1 semi industrial interspersed with residential and commercial neighborhoods, and 1 absolute industrial zone) and a residential neighborhood all of which were centrally located and paved neighborhoods.

Roadmap of Write-up

This write up is presented in 4 sections as follows:
It begins with an **Introduction** which is followed by a **Literature Review** of key concepts. After the literature review, the methods used are examined in the **Methodology** section which is tailed by **Results and Discussion**. The Conclusion then ends the write up. The Reference list immediately follows the conclusion. Acknowledgement is the last but not the list item in the write-up.

**Literature Review**

Airborne particulate matter (PM) is a complex mixture of thousands of organic and inorganic species that emerge from a wide range of natural and anthropogenic sources (Seinfeld and Pandis, 2006).

Some particulates occur naturally, originating from volcanoes, dust storms, forest and grassland fires, living vegetation and sea spray. Human activities, such as the burning of fossil fuels in vehicles (Omidvarborna et al., 2015), stubble burning, power plants, wet cooling towers in cooling systems and various industrial processes, also generate significant amounts of particulates. Coal combustion in developing countries is the primary method for heating homes and supplying energy. Because salt spray over the oceans is the overwhelmingly most common form of particulate in the atmosphere, anthropogenic aerosols currently account for about 10% of the total mass of aerosols in our atmosphere.

According to Seinfeld and Pandis (2006); Brook et al. (2010); Heal et al. (2012) and Manisalidis et al., 2020, air pollutants may either be emitted directly into the atmosphere (primary pollutants) or formed within the atmosphere itself through chemical reactions and physical processes (secondary pollutants). Heal et al. (2012), further classifies them as inhalable, thoracic and respirable dust fractions depending on the depth of penetration of the particle into the respiratory system. The inhalable dust fraction with a size threshold of about 50µm can be captured by inhalation in the nasal cavity (easily filtered by cilia or mucus). The dust fraction reaching all the way to the lungs (lower respiratory tract) is the thoracic dust fraction. These are particles ≤ 10 but > 2.5µm (Boman et al., 2010; Fortoul et al., 2012; Manisalidis et al., 2020), and the fine dust that can penetrate even further into the bronchioles and alveoli (gas exchange region) is known as the respirable dust fraction. These particles are not ejected by breathing out, coughing, or expulsion by mucus, and approximates a particle size threshold of about 3.5 – 4µm. In effect, they are < 2.5µm (WHO, 2003; Boman et al., 2010; Fortoul et al., 2012; Heal et al., 2012), and are capable of reaching the gas exchange surfaces of the alveoli (Heal et al., 2012).

**Effects of Particulate Matter**

**Health Effects**

Particulates are the deadliest form of air pollution and of particular importance when human health is concerned due to their ability to penetrate deep into the alveolar region of the lungs and blood streams unfiltered, causing permanent DNA mutations, heart attacks, respiratory disease, and premature death (Boman et al.,
Inhalation of PM in the atmosphere can directly or indirectly lead to or deteriorate various symptoms/diseases by triggering inflammation in the smaller airways leading to the exacerbation of asthma and bronchitis (Brook et al., 2004; Samet and Krewski, 2003 Ann et al., 2018 Manisalidis et al., 2020). Other health symptoms include hay fever, increased respiratory symptoms, pulmonary inflammation, reduced lung function, and cardiovascular diseases. PM can reduce lung functioning and can cause or aggravate respiratory conditions, and increase the long term risk of lung cancer or other lung disease such as emphysema, bronchiectasis, pulmonary fibrosis, and cystic lungs (Samet and Krewski, 2003; Begum et al., 2007; Kuan et al., 2017; Lindsay and Xiaohong, 2018). As stated by Samet and Krewski (2003) PM leads to high plaque deposits in arteries, causing vascular inflammation and atherosclerosis - a hardening of the arteries that reduces elasticity, which can lead to heart attacks and other cardiovascular problems. Air pollutants have been linked with endothelial dysfunction and vasoconstriction, increased blood pressure (BP), prothrombotic and coagulant changes, systemic inflammatory and oxidative stress responses, autonomic imbalance and arrhythmias, and the progression of atherosclerosis (Brook et al., 2010). Samet and Krewski (2003) suggest that the mechanisms of formation (e.g. nucleation, coagulation and condensation for the finer fraction or the more abrasive formation systems of the coarser fraction) may also have implications for respiratory related health effects.

The health risk from particulates is a function of the size and concentration of the dose inhaled, the surface area and the chemical composition (Donaldson and Tran, 2002; Noel de Nevers, 2000; WHO, 2006; Heal et al., 2012; Ann et al., 2018; Manisalidis et al., 2020).

Associations between exposure to PM, pregnancy and neo-natal outcomes have been reviewed by WHO (WHO, 2005) and others (Heal et al., 2012). Research suggests health impacts of air pollution in the early stages of human development (Samet and Krewski, 2003; WHO, 2006). In one study, low ambient air pollution concentrations were associated with adverse pregnancy outcomes including low birth weight, preterm birth, and intrauterine growth retardation (Liu et al., 2003). In another study, particles were found to be positively associated with first hospitalizations due to respiratory disease in early childhood (Yang et al., 2003).

Effects on Vegetation

The effects of PM are not only limited to human health but extend widely to plant productivity and survival (Woo et al., 2007). Kuwar et al. (2018) states that air pollution can directly affect plants via leaves. Although plants are very important to maintain ecosystem health, they may, however, be severely affected by PM pollution (Agbaiire and Esiefierenrhe, 2009; Shweta, 2012; Rai, 2013; Panda and Rai, 2015). According to Liu and Ding, 2008, particulate air pollution can directly affect plants via leaves or indirectly via soil acidification. When exposed to airborne pollutants, most plants experience physiological changes before exhibiting visible damage to leaves (Cotrozzi et al., 2017). Foliar surface of plants acts as a sink for PM deposition and through their deposition they show
specific morphological, physiological, and biochemical responses inducing structural and functional changes (Panda and Rai, 2015; Garrec, 2020). Hogan (2010) explains that PM can also clog stomata of plants interfering with photosynthesis functions. In this manner high PM concentrations in the atmosphere can lead to growth stunting or mortality in some plant species.

Meteorological Implications

According to Tai et al. (2012), Lecoeur et al. (2012) and Li et al. (2020), the fate of air pollutants is influenced by the movements and characteristics of the air mass into which they are emitted. The measurements of wind speed and direction, temperature, humidity, rainfall and solar radiation are important parameters used in the study of air quality and can assist in furthering understanding of the chemical reactions that occur in the atmosphere (Lecoeur et al., 2012; Wei Dai et al., 2012).

As stated by Tai et al. (2010) and Li et al. (2020), PM$_{2.5}$ concentrations depend on meteorological conditions, suggesting that climate change could have significant effects on PM$_{2.5}$ air quality and vice versa. PM is comprised of many different species, and meteorology can have complex effects on total PM concentrations due to its impacts on individual species (Dawson et al., 2007; Zhou et al., 2020). Aerosol SO$_4^{2-}$ concentrations depend on the temperature-dependent oxidation of SO$_2$ in both the gas and aqueous phases, and sunlight intensity (Seinfeld and Pandis, 2006 and Dawson et al., 2007; Zhou et al., 2020). On the other hand, concentrations of semi-volatile NO$_3^-$ and organic aerosols are temperature and relative humidity dependent; they can also vary with the amount of oxidants present, which is linked to photolysis rates and, therefore, cloud cover (Dawson et al., 2007). Tai et al. (2010), Dawson et al. (2007) and Tsagaridis and Kanakidou (2007) report that SO$_4^{2-}$ concentrations are expected to increase with increasing temperature due to faster SO$_2$ oxidation, but semi-volatile components such as NO$_3^-$ and organics are expected to decrease as they shift from the particle phase to the gas phase at higher temperature.

Higher relative humidity (RH) promotes the formation of ammonium nitrate, but an increase in precipitation causes a decrease in all PM$_{2.5}$ components through scavenging and since all species have wet deposition as a sink, precipitation is expected to have a significant effect on aerosol concentrations (Dawson et al., 2007). During a study by Dawson et al. (2007), it was observed that the changes in PM$_{2.5}$ resulted even in areas with little or no base-case precipitation indicating that changes in precipitation in upwind areas affected PM$_{2.5}$ concentrations in downwind areas. Seinfeld and Pandis (2006) conclude that changes in absolute humidity have the largest effects on concentrations of ammonium nitrate aerosol with concentrations increasing with increased absolute humidity and that increases in humidity shift the equilibrium of the ammonia-nitric acid system toward the aerosol phase, resulting in higher concentrations of ammonium nitrate aerosol.

Finally, mixing and dilution influence PM concentrations, so wind speed and mixing height are expected to have an impact as well. According to Tai et al. (2009), if the air is calm and pollutants cannot disperse then the concentration of
these pollutants will build up. Conversely, if a strong, turbulent wind is blowing any pollution generated will be rapidly dispersed into the atmosphere resulting in lower pollutant concentrations in the air. Wind speed changes affect all species that comprise PM$_{2.5}$, with increases in wind speed generally leading to decreases in PM$_{2.5}$ concentrations, and decreases in wind speed generally leading to increases in PM$_{2.5}$ (Dawson et al., 2007; Ya-Gao et al., 2019). According to Brook et al., (2010), increases in wind speed leads to changes in advection and transport resulting in decreases in PM$_{2.5}$ concentrations.

**Objectives**

This study seeks to investigate and evaluate the level of PM in the industrial town of Douala in Cameroon. The objectives of the study were to analyse and quantify PM$_{2.5}$ in terms of mass and mass concentration and the elemental composition of the PM found in Douala. The study also focused on determining the influence of meteorological parameters on PM$_{2.5}$ concentration in Douala, embarked on apportioning sources to the different PM components that would be identified, and analyzing the variation of fine particles with meteorological parameters, and determine the sources of the PM$_{2.5}$ in the area.

**Methodology**

**Sample Collection**

Sampling was done using an electrically powered cyclonic sampler (Casella Group Ltd) capable of collecting PM in PM$_{2.5}$ - 10 size fractions. The cyclone separates the PM$_{2.5}$ particles from the air stream and impacts them on polycarbonate filters. Operating at a constant volumetric flow rate of 3L/min, PM$_{2.5}$ particles were collected for a period of 1 month. The flow through the cyclone was kept constant by a critical orifice (accuracy of ± 15%) to maintain a particle cut off diameter of 2.5µm. Purposefully, samples were collected at 3 sites in the industrial town of Douala (Figure 1): Site 1, the Bonaberi industrial zone (longitude 09º74” East and latitude 04º09” North), Site 2, the Bassa industrial zone (longitude 09º68” East and latitude 04º07” North) and Site 3, the Bonamoussadi residential zone (longitude 09º75” East and latitude 04º04” North). At site 1, the sampler was placed at a height of 8.5m above ground with the intake nozzle placed 1.5m above the platform on which the sampler was placed. The nozzle was placed such that airflow was unobstructed (at all sites) about 200m away from the industrial area and 5m away from the road. The Bassa site saw similar sampling conditions. The sampler was placed facing the industrial zone but away from the road 100m away. It was placed 8.0m above ground and 80m away from the railway. At site 3 the sampler was placed on the flat roof 5m above ground with the nozzle position 2m above the roof and 100m away from the roadside. The sampler was placed such that air flow was unobstructed. Effective sampling time was ± 24hours.
Particle collection was done on 25mm diameter Teflon filters with a pore size of 0.4µm. The polycarbonate filters were initially preconditioned at 45% relative humidity and 20°C before they were weighed and placed in Petri dishes. After sampling, the filters were again placed and stored in the same dishes. An OHAUS Adventurer Pro electronic analytical microbalance with a sensitivity of 0.0001 mg was used for gravimetric determination of the sampled particle mass. The set up was mounted at each location for 9 sampling days. Since the same setup was used during the whole campaign the different samples can be compared with each other without being influenced by possible differences in sampling flow.

Figure 1. Map of Study Area showing Sampling Sites in Douala

Sample Analysis

The samples were analyzed for PM mass concentration, elemental composition and black carbon. A principal component analysis (PCA) was conducted to apportion PM sources.

PM Mass Concentration

Gravimetric analysis was performed to determine the mass concentration of the sample aerosol.

The total volume of air sampled was determined from the volumetric flow rate of 3L/min and sampling time in minutes. The concentration of PM$_{2.5}$ in the ambient air is computed as total mass of collected particles divided by the volume of air sampled in actual conditions. The concentrations are expressed in micrograms per actual cubic meter (µg/m$^3$). The equation governing the gravimetric analysis is given below:
\[ C_{PM} = \frac{M}{V} \]

Where,
1. \( C_{PM} \) = PM Mass Concentration
2. \( M \) = Net mass of the particulate matter collected on the sample filter
3. \( V \) = The volume of air sampled

**Elemental Analysis**

Samples obtained were analyzed for elemental composition by Energy Dispersive X-Ray Fluorescence (EDXRF) spectrometry (Van Grieken and Markowicz, 1993). The spectrometer based on a three-axial geometry consisted of a Siemens Mo-anode X-ray tube with a Mo secondary target that facilitated a good signal to background ratio giving low detection limits (Table 2), and a Kevex Si (Li) detector. According to Boman et al (2005) and Gatari et al (2006), the spectrometer was operated at 50kV and 25mA and the samples were analyzed for 1000s. Sample elemental spectra were obtained and evaluated by a quantitative x-ray analysis system (QXAS) software provided by the International Atomic Energy Agency (IAEA) laboratories, Seibersdorf, Austria. Atmospheric concentrations and detection limits (DLs) were determined and several of the elements below detection limits were excluded from analysis.

**Black Carbon Determination**

BC concentrations were determined by a black smoke detector model FH 621-N (ESM Emberline, Erlangen, Germany). In this device the samples were illuminated by red light emitting diodes and the reflected light then detected and given as a voltage reading. These voltage readings were later recalculated into BC concentrations.

**Principal Component Analysis**

Factor analysis with Principal Components as extraction method known as Principal Component Analysis (PCA) in air quality studies is widely used to provide information on PM or gaseous pollutant sources (Querol et al., 2001; Amodio et al., 2010). The PCA technique identifies components that explain the common variation pattern of the included variables (elements, and BC) based on the principle that elements with similar concentration patterns most likely originate from a common source. The components are identified by the PCA, and possible sources of the components ascribed. Values < 0.3 have low loading, those between 0.3 and 0.6 are considered to have moderate loadings, those with 0.8 are said to be moderately high loadings and values > 0.8 are considered as high loadings (Boman et al., 2009).

**Meteorological Conditions**

Since PM\(_{2.5}\) concentrations are strongly dependent on meteorological conditions, it is important to investigate the relationships between PM\(_{2.5}\) and meteorological parameters (Lecoeur et al., 2012). The meteorological information during the measurement campaign was obtained from the Douala Meteorological...
centre which records such data for the entire city. The website http://wunderground.com was also valuable in getting certain daily variations for some climate parameters.

Results and Discussion

Mass and Mass Concentration

The mean mass and mass concentration of PM collected from the 3 sites is as shown on Table 1.

**Table 1(a). Mass and Mass Concentration for Bonamoussadi**

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>Mass Concentration (µg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.0009</td>
</tr>
<tr>
<td>Standard Dev.</td>
<td>0.000327</td>
</tr>
<tr>
<td>Range</td>
<td>0.0003 – 0.0014</td>
</tr>
<tr>
<td>Median</td>
<td>0.001</td>
</tr>
</tbody>
</table>


**Table 1(b). Mass and Mass Concentration for Bonaberi**

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>Mass Concentration (µg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.0012</td>
</tr>
<tr>
<td>Standard Dev.</td>
<td>0.000856</td>
</tr>
<tr>
<td>Range</td>
<td>0 – 0.0025</td>
</tr>
<tr>
<td>Median</td>
<td>0.00135</td>
</tr>
</tbody>
</table>


**Table 1(c). Mass and Mass Concentration for Bassa**

<table>
<thead>
<tr>
<th>Mass (g)</th>
<th>Mass Concentration (µg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.00115</td>
</tr>
<tr>
<td>Standard Dev.</td>
<td>0.000475</td>
</tr>
<tr>
<td>Range</td>
<td>0.0003 – 0.002</td>
</tr>
<tr>
<td>Median</td>
<td>0.00115</td>
</tr>
</tbody>
</table>


The cumulative mean concentration for all sites is 252 ± 130.8µg/m$^3$ which is relatively higher than the WHO Guideline of 25 µg/m$^3$ for PM$_{2.5}$ (24-hour mean), as stated by Heal et al. (2012). The daily variation in particle mass concentration of PM$_{2.5}$ in Douala is clearly shown in Figure 2 below.
The huge population of the city, the wide range of commercial and industrial activities, variety of old and new, maintained and poorly maintained vehicles, large scale two wheel activities, and the dependence of the population on biomass significantly contribute to the high value of PM$_{2.5}$ mass concentration. Open burning and the high dependence on fuel wood and charcoal for domestic and commercial purposes significantly contributes the high BC concentrations for all sampling sites.

**Elemental Analysis**

EDXRF was run for 22 elements, and a total of 12 elements were identified (above detection limits as shown in Table 2), and quantified in most of the samples; Cl, K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, Br, Sr, and Pb (Table 2).

**Table 2. Detection Limits (DL) in µg/m$^3$ for the Analysed Elements**

<table>
<thead>
<tr>
<th>Elt</th>
<th>Cl</th>
<th>K</th>
<th>Ca</th>
<th>Ti</th>
<th>Mn</th>
<th>Fe</th>
<th>Ni</th>
<th>Cu</th>
<th>Zn</th>
<th>Br</th>
<th>Sr</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL</td>
<td>0.02</td>
<td>0.02459</td>
<td>0.00763</td>
<td>0.002277</td>
<td>0.002214</td>
<td>0.000220</td>
<td>0.0002</td>
<td>0.000159</td>
<td>0.0000724</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.000269</td>
</tr>
</tbody>
</table>

NB: Three axial geometry with Mo secondary target. X-ray tube operated with 50kV and 25mA. Lifetime of 1000s. A collection time of 24h.

Full campaign concentration means with standard deviations in µg/m$^3$ for the analysed elements and the PM$_{2.5}$ mass concentrations at the three sites including BC concentrations in µg/m$^3$ are given in Table 2. Reported elemental concentrations are those above DL and blank filter concentrations. N is the number of samples with concentration above DL. DL for analysed elements ranged from
0.001 µg/m$^3$ for Br and Sr to 0.12 µg/m$^3$ for Cl as shown on table 3 which shows the average elemental concentrations for the entire city while figure 3 shows how the elemental concentration varied at different sites.

Table 3. Average Elemental Concentrations for the Entire City

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Average (µg/m$^3$)</th>
<th>Average (ng/m$^3$)</th>
<th>N (Max = 24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle mass concentration (µg/m$^3$)</td>
<td>0 – 578.7</td>
<td>251.4 ± 133.7</td>
<td>251400 ± 133700</td>
<td>24</td>
</tr>
<tr>
<td>Black Carbon</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>0.131 - 0.760</td>
<td>0.347 ± 0.189</td>
<td>347 ± 189</td>
<td>9</td>
</tr>
<tr>
<td>K</td>
<td>0.048 - 0.507</td>
<td>0.164 ± 0.103</td>
<td>167 ± 103</td>
<td>19</td>
</tr>
<tr>
<td>Ca</td>
<td>0.027 - 0.810</td>
<td>0.190 ± 0.195</td>
<td>190 ± 195</td>
<td>23</td>
</tr>
<tr>
<td>Ti</td>
<td>0.008 - 0.085</td>
<td>0.029 ± 0.020</td>
<td>29 ± 20</td>
<td>18</td>
</tr>
<tr>
<td>Mn</td>
<td>0.003 - 0.126</td>
<td>0.017 ± 0.033</td>
<td>17 ± 33</td>
<td>13</td>
</tr>
<tr>
<td>Fe</td>
<td>0.035 - 0.917</td>
<td>0.248 ± 0.216</td>
<td>248 ± 216</td>
<td>24</td>
</tr>
<tr>
<td>Ni</td>
<td>0.003 - 0.009</td>
<td>0.005 ± 0.002</td>
<td>5 ± 2</td>
<td>4</td>
</tr>
<tr>
<td>Cu</td>
<td>0.002 - 0.013</td>
<td>0.005 ± 0.003</td>
<td>5 ± 3</td>
<td>17</td>
</tr>
<tr>
<td>Zn</td>
<td>0.004 - 1.777</td>
<td>0.296 ± 0.469</td>
<td>296 ± 469</td>
<td>24</td>
</tr>
<tr>
<td>Br</td>
<td>0.017 - 0.040</td>
<td>0.022 ± 0.005</td>
<td>22 ± 5</td>
<td>24</td>
</tr>
<tr>
<td>Sr</td>
<td>0.001 - 0.022</td>
<td>0.004 ± 0.005</td>
<td>4 ± 5</td>
<td>15</td>
</tr>
<tr>
<td>Pb</td>
<td>0.007 - 2.075</td>
<td>0.292 ± 0.48</td>
<td>292 ± 480</td>
<td>24</td>
</tr>
</tbody>
</table>


Figure 3: Variation of Elemental Concentration at Different Sites

For Bonaberi, Ca, Fe, Zn, Br and Pb were present in all samples while for Bassa only Fe, Zn, Br and Pb were identified in all samples. Cl and Ni have the lowest frequencies of occurrence with Cl appearing only once in Bonamoussadi, Ni appearing twice in Bonamoussadi, once in Bonaberi and Bassa with the highest concentration recorded in Bassa.
All concentrations but for Fe, Zn and Pb have concentrations < 0.3µg/m³ for
Bonaberi. But for Cl, all other elements have concentrations < 0.3µg/m³ for
Bonamoussadi and Bassa. Ca presents relatively high concentrations in Bonaberi
than for the other zones most probably due to the presence of the cement industry
which is present in Bonaberi and absent in the other zones.

While the concentration of Br is relatively low for the other zones,
Bonamoussadi presents a higher Br concentration. The high Br concentration
could be explained by a high input of particles from biomass burning, since Br can
be tracer element for pyrogenic biomass burning.

The possible contribution of Br from sea spray or some combustion source
especially vehicle exhaust cannot be excluded (Boman et al., 2009). Apart from
Cl, K and Ca which are higher in Bonamoussadi than in Bassa, Bonamoussadi
generally has lowest concentrations. It can then be concluded that Bonaberi has
highest elemental concentrations followed by Bassa then by Bonamoussadi. The
industrial zones therefore contain more PM₂.⁵ than the residential zone.

The lone appearance of Cl in Bonamoussadi indicates there is no local source
in that locality. The high Cl concentration could either be from a sporadic source
or blown in by the wind. PM concentrations here seem to be higher than for
Bonamoussadi. Ca, Fe, Zn and Pb have highest concentrations as can be seen in
Figure 3. Unlike in Bonamoussadi, Ca has peaks higher than the 0.3 line which
can be explained by the presence of the cement industry in Bonaberi. Cl also
presents concentrations higher than the other sites.

The relatively high concentration of Pb especially in Bonaberi can be
accounted for by the presence of fuel from unofficial markets (locally known as
“fungeh”). Leaded paint is also being scrapped from walls and spread in both old
and new construction sites and also at the shipyard (eye witness account). Chronic
exposure to low concentrations of Pb is very dangerous and can lead to reduction
of intelligence, increased blood pressure and a range of behavioral and
developmental effects (WHO, 2005).

The results show a large variation in sample mass, BC concentration as well
as in the concentrations of the analyzed elements. A look at the individual samples
from the different sites (Figure 4) signifies that the variation of the different
constituents does not show the same pattern. This adds to the picture of different
sources for different pollutants and to the influence of meteorology on PM
concentration. The different patterns are as shown in the Figure 4a-c.
Figure 4(a). Individual Element Pattern for Elements Found in PM$_{2.5}$ in Bonamoussadi

Figure 4(b). Individual Element Pattern for Elements Found in PM$_{2.5}$ in Bonaberi
Very high concentrations of BC are recorded for Bonaberi, high concentrations for Bonamoussadi and averagely high concentrations for Bassa. The mean concentration of Bonaberi, $3.17 \pm 2.376 \, \mu g/m^3$ as opposed to $1.42 \pm 0.459 \, \mu g/m^3$ for Bonamoussadi and $1.10 \pm 1.566 \, \mu g/m^3$ for Bassa is relatively very high. The sampling site for Bonaberi is the gateway to and away from the Wouri Bridge hence very dense traffic for most parts of the day hence emissions from vehicle exhaust can explain the high BC concentration. The industrial zone also has very high dependence on fossil fuel for energy production. Bonamoussadi concentrations can be due to the burning of biomass for domestic purposes while vehicle emissions cannot be ignored. Traffic also accounts for that of the Bassa area which is a gateway from Douala to Yaoundé with high traffic at Ndokotti Market. Open burning and the high dependence on fuel wood and charcoal burning for domestic and commercial purposes significantly contribute the high BC concentrations for all the areas.

**Factor Analysis**

Three components were extracted by the analysis explaining a total of 76.8% variance for the whole data set as shown on Table 4. The first component is characterized by high loadings of Fe, K, Zn, and moderately high loadings for Cu, Cl, Sr, Br, Ti, and Ca. This component accounts for 50.5% of the total variance obtained. The component could be interpreted as a combination of geological (soil/crust) origin and combustion aerosols. There is a combination of high and moderately high loadings for elements which are derived from these sources. K and Fe for example have high loading and indicate soil originated aerosols, Ti and Ca have moderately high loadings and indicate soil originated aerosols while Zn with High loading indicate industrial activity (Boman et al., 2009) especially metallurgical activities (Heal et al., 2012). The moderately high Cl and Br loadings also indicate industrial combustion. Zn and Fe could also be emitted from
lubricating oil additives (used in two-stroke engine where engine oil is mixed with fuel), combustion of impure fuel, vehicle engine and brake tire wear.

Table 4. Component Matrix for Source Apportionment for Elements in Air Samples from Douala

<table>
<thead>
<tr>
<th>Elements</th>
<th>Components 1</th>
<th>Components 2</th>
<th>Components 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl</td>
<td>.754</td>
<td>-.021</td>
<td>-.518</td>
</tr>
<tr>
<td>K</td>
<td>.882</td>
<td>.367</td>
<td>-.130</td>
</tr>
<tr>
<td>Ca</td>
<td>.668</td>
<td>.538</td>
<td>.141</td>
</tr>
<tr>
<td>Ti</td>
<td>.721</td>
<td>.050</td>
<td>.517</td>
</tr>
<tr>
<td>Mn</td>
<td>.345</td>
<td>.748</td>
<td>.289</td>
</tr>
<tr>
<td>Fe</td>
<td>.946</td>
<td>-.207</td>
<td>-.063</td>
</tr>
<tr>
<td>Cu</td>
<td>.779</td>
<td>.147</td>
<td>-.191</td>
</tr>
<tr>
<td>Zn</td>
<td>.818</td>
<td>-.158</td>
<td>-.150</td>
</tr>
<tr>
<td>Br</td>
<td>.727</td>
<td>-.357</td>
<td>.168</td>
</tr>
<tr>
<td>Sr</td>
<td>.753</td>
<td>-.242</td>
<td>-.358</td>
</tr>
<tr>
<td>Pb</td>
<td>.394</td>
<td>-.730</td>
<td>.394</td>
</tr>
<tr>
<td>BC</td>
<td>.450</td>
<td>-.049</td>
<td>.581</td>
</tr>
</tbody>
</table>

The first component has high loading for all detected elements but for Mn, Pb and BC. Zn compounds are extensively employed as lubricants, antioxidants and as detergent/dispersant improvers for lubricating oils (Begum et al., 2007). The high and moderately high loadings are of more mixed character, possibly representing both soil and combustion origin. To confirm this mixed character, Fe, K, and Ca are characteristic to road dust attributed to diesel vehicle emissions. The industrial and petrochemical waste managing companies that incinerate most of these wastes could also be a significant source for these elements in the atmosphere.

The second component is characterized by moderate loading from Mn, and this component accounts for 15.0% of the total variance obtained. Moderate loadings of Mn bear sign of aerosol from the metallurgical industry (Heal et al., 2012). This could be confirmed by the moderate loading of Ca in this component. Other activities generating Mn include vehicle engine, brake and tyre wear, and during combustion of impure fuel (particularly coal), and fuel and lubricating oil additives (Heal et al., 2012). Nonetheless, Mn and Ca are typical mineral elements and consequently, this factor could be associated with the crustal fraction of PM$_{2.5}$ (Heal et al., 2005). The presence of these elements in PM$_{2.5}$ could mainly be a result of local and regional dust re-suspension by wind, convection and other natural processes. However, if the emissions from incomplete and complete combustion of biomass have different sources, this could explain the appearance in two different components in the analysis.
The third component had moderate loading for BC accounting for 11.4% of the obtained variance. BC is a good marker for combustion-derived component of airborne particles. It is also a good marker for traffic-related PM pollution (Heal et al., 2012).

PCA for individual sampling sites showed same results as above implying that the individual sites have similar sources of particulate pollution.

Ni which was not included in the PCA due to its being below detection limits for most samples mainly comes from dust and re-suspended soil particles. It is also a tracer for the combustion of heavy fuel oil (Boman et al., 2010).

*Influence of Meteorology on PM Concentration*

Diurnal temperatures varied between 23°C and 31°C and relative humidity between 81 and 95%. Winds in Douala were westerly, showing a diurnal pattern with gusts of up to 10m/s during daytime, while evenings and nights were generally calmer with very stable atmospheric conditions.

Scattered plots showing variation of meteorological variables with the elemental concentration for the sampling period are given in the Figure 5.

**Figure 5.** Variation of PM Mass Concentration with Meteorological Parameters: (A) with Temperature, (B) with Rainfall, (C) with Wind Speed and (D) with Relative Humidity
Trends for the plot for temperature against mass concentration (A) show that as temperature increases in Bonaberi, the mass concentration reduces while mass concentration increases with increase in temperature for both Bonamoussadi and Bassa. These variations can be explained by the chemical species present in the PM$_{2.5}$. The mass concentration reduction with increasing temperature for Bonaberi could be explained using the species present in the PM$_{2.5}$. This trend may indicate the dominance of nitrates in this area since nitrates are semi-volatile. It could also indicate the dominance of primary particulates in this region (Seinfeld and Pandis, 2007).

For Bonamoussadi and Bassa, mass concentration increases with increasing temperature indicating the probable presence of sulphates and dust. According to Seinfeld and Pandis (2007), the oxidation of SO$_2$ to SO$_4^{2-}$ is temperature dependent and increases as temperature increases thus increasing the aerosol concentration. This also indicates that these two areas are dominated by secondary particulates. From literature, one of the precursor gases for the formation of secondary particulates is SO$_2$ thus confirming the above assertion. On another hand, these variations can be explained by wind speeds and direction. The wind blows away from Bonaberi hence transporting away a bulk of the mass of particles with it, whereas for Bonamoussadi and Bassa, the wind blows to their direction bringing in more particles from the upwind. This confirms the theories of Brook et al. (2004), Dawson et al. (2007) and Tai et al. (2009).

Mass concentration of PM$_{2.5}$ shows a slight decrease with increasing rainfall for Bassa. A slight increase is noticed for Bonaberi and a sharp increase for
Bonamoussadi. This can be explained by the nature of rainfall which is predominantly thunderstorms. Depending on the strength of the wind during the storm, the process of wet deposition can be counteracted and the particles blown away in the wind faster than they are deposited or washed out by the rain. In this case, the particles are blown downwind and mass concentration can then increase in the downwind area with increasing rainfall. This confirms Dawson et al. (2007)’s conclusion that changes in precipitation in upwind areas affect PM$_{2.5}$ concentrations in downwind areas and also explains the slight increase in PM mass concentration in Bonaberi as rainfall increases. The degree of change could be affected by the aerosol concentration of the upwind area.

PM mass concentration increases with increasing wind speed increases in all the locations contradicting the theories of Dawson et al. (2007) and Tai et al. (2009) which states that if the air is calm and pollutants cannot disperse then the concentration of these pollutants will build up. Conversely, if a strong, turbulent wind is blowing any pollution generated will be rapidly dispersed into the atmosphere resulting in lower pollutant concentrations in the air. This contradicting behaviour could be explained by the thunderstorm effect. However, it should be noted that the month of November which should be dry recorded quite some rainfall which could affect the behaviour of aerosols. In the dry season, there is the general tendency of particles to build up. And if suddenly strong winds and heavy rainfall come to play, patterns could be altered.

PM$_{2.5}$ mass concentration generally decreases as relative humidity increases. According to Dawson et al. (2007) this trend can be explained by the different species in the PM$_{2.5}$. Nitrates are semi-volatile thus, when relative humidity and temperature increase, they are taken out of the atmosphere by volatilisation hence reducing the mass concentration of PM$_{2.5}$. This trend could be an indication that the PM$_{2.5}$ in these areas is dominated by primary particulates. Tsigaridis and Kanakidou (2007) states that nitrates shift from particle phase to gas phase as temperature and relative humidity increase.

Conclusion

PM$_{2.5}$ for the city of Douala was collected over a 24hr sampling period and analysed for mass, mass concentration and elemental composition. The cumulative mass concentration of 252 ± 130.8µg/m$^3$ which is critically higher than the WHO standard of 25µg/m$^3$ was recorded. Cl, K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, Br, Sr, and Pb were identified in the PM collected. The high concentration of Pb indicated the use of leaded fuels and/or paints. The industrial zones exhibited higher PM concentrations than the residential areas. Meteorological parameters greatly influenced the PM concentration. However, the “thunderstorm effect” counteracted the normal variation of PM$_{2.5}$ with wind speed and precipitation.

Diurnal patterns in concentrations suggested a common PM source. From PCA it was concluded that anthropogenic activities like traffic, biomass burning and industrial activities were the major PM sources. Old fleet and poorly maintained vehicles exacerbate the situation. Despite the high emission from these
sources, natural sources such as sea spray and windblown dust significantly contribute to the PM load of this city.

Conclusively, the results presented in this study indicate that the majority of the Douala inhabitants are exposed to high air pollution levels in their everyday life.

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