Research article
Assessing anthropogenic contribution to PM$_{2.5}$ from an urban residential area of Lagos, Nigeria using aliphatic hydrocarbon compounds as indicators

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Abstract

Aliphatic hydrocarbons in PM$_{2.5}$ samples from a residential area of Lagos, Nigeria, were quantified using a Curie-point pyrolysis–gas chromatography–mass spectroscopy (CPPGC/MS). The total concentrations of ∑n-alkanes (C$_{20}$-C$_{34}$), hopanes ($\sum_4$Hopanes), and steranes ($\sum_3$Steranes) ranged from 1.8 to 146.6 ng m^{-3} (avg. 43.6 ± 35.1 ng m^{-3}), 0.0 to 89.9 ng m^{-3} (avg. 18.7 ± 25.9 ng m^{-3}), and 0.0 to 26.0 ng m^{-3} (avg. 3.3 ± 6.7 ng m^{-3}), accounting for 0.2%, 0.1%, and 0.01% of the total PM$_{2.5}$ mass concentrations, respectively. They also accounted for, 1%, 0.4% and 0.1% of the organic matter content, respectively, making them non-negligible component of the organic matter in this region. An evaluation of the n-alkanes source diagnostic indices revealed that engines powered by gasoline and diesel were the main sources of particulate matter aliphatic hydrocarbons in this area of Lagos, consistent with the results obtained from steranes and hopanes profiles. Based on the air mass trajectories, both local and regional air mass transports showed a significant influence on the amounts of carbonaceous materials and aliphatic hydrocarbon compounds arriving at the study site. The results from this study established the occurrence of anthropogenic air pollution in Lagos residential area with a major contribution from petrogenic sources.

Keywords

Introduction

Atmospheric particulate matter (PM) with an aerodynamic diameter of 2.5 μm or less (PM$_{2.5}$) is considered a major contributor to severe air pollution and has significant impacts on human health, atmospheric visibility and climate (Russell and Brunekreef, 2009; Javed et al., 2019; Tian et al., 2020; Sun et al., 2021). The composition of PM$_{2.5}$ is very complicated and includes organic carbon (OC) and elemental carbon (EC), often referred to as carbonaceous components, trace metals, inorganic salts and some specific organic compounds such as aliphatic hydrocarbons including n-alkanes, steranes and hopanes, n-alkanoic acids and polycyclic aromatic hydrocarbons (PAHs) (Mandalakis et al., 2002; Javed et al., 2019; Sun et al., 2021). However, the most prevalent and significant class of organic compounds in the atmosphere are the aliphatic hydrocarbons (Fu et al., 2008; Ren et al., 2016; Boreddy et al., 2018). Due to their specificity, hydrophobicity, and prolonged persistence in the environment, these aliphatic hydrocarbon compounds have

been used as organic molecular markers for pollution source identification (Simoneit et al., 1991; Mudge and Duce, 2005; Andreou et al., 2007; Javed et al., 2019; Sun et al., 2021). For example, n-alkanes primarily come from both anthropogenic and biological sources, such as petroleum residue, diesel engine exhaust (Simoneit,1984), and biomass burning (Simoneit and Elias, 2000, 2001), and also from terrestrial plant wax, fungi, bacteria, algae, and plankton (Brown et al., 2002). Additionally, plant wax n-alkanes are employed directly as a proxy for both the atmospheric transport and genesis of organic aerosol (OA) in the atmosphere (Tang et al., 2006; Lyu et al., 2017). Hopanes and steranes are ubiquitous in crude petroleum and are enhanced in the lubricating oils used in diesel and gasoline-powered motor vehicles, and their existence in the environment confirms the contribution of the burning of fossil fuels in the area (Simoneit et al., 2004; Rushdi et al. 2017; Javed et al., 2019). EC is mainly emitted from anthropogenic combustion sources, whereas

OC, as a complex mixture of many groups of compounds, has both primary and secondary origins. Primary organic carbon (POC) is generated during the combustion process, while secondary organic carbon (SOC) is produced in the atmosphere through the gas to particle conversion processes of volatile precursors. Exposure to high levels of these urban carbonaceous components has been linked with cardiovascular mortality and morbidity (Samara et al., 2013).

At present, improving the ambient air quality is one of Lagos's greatest environmental challenges. Studies relating to the PM$_{2.5}$ pollution status in Lagos have been reported by various authors (Ezeh et al., 2012; Obioh et al., 2013; Owoade et al., 2013; Ezeh et al., 2014; Alani et al., 2019; Zeng et al., 2019). However, reports have focused on the mass concentrations and elemental characterisation of PM$_{2.5}$, while information on specific organic compound classes such as aliphatic hydrocarbons in PM$_{2.5}$ that can be utilised as source markers in identifying the primary sources of organic aerosols (OA) are very scarce. For instance, Ezeh et al. (2012) and (2014) determined PM$_{2.5}$ mass concentrations at different locations in Lagos during the rainy season. Although their results showed that PM$_{2.5}$ mass concentrations were below the World Health Organization (WHO) limit of 25 µg m^{-3}, they argued on the basis of correlation and enrichment factor analyses that most trace elements in PM$_{2.5}$ originated from anthropogenic sources. Similarly, Owoade et al. (2013) determined the PM$_{2.5}$ mass concentrations from different classes of receptor sites in Lagos. They showed that some residential areas have higher PM$_{2.5}$ levels due to contributions from local sources and transport of pollutants from neighbouring sites more than industrial areas. Common anthropogenic sources for PM$_{2.5}$ in their study include traffic-related, traffic emissions, marine salt, and industrial emissions based on the principal component factor analysis (PCFA) of the detected elements. More recently, Zhen et al. (2019) reported the chemical characteristics of PM$_{2.5}$ based on PM$_{2.5}$ mass concentrations, OC, EC, water-soluble ions and elemental compositions. According to their results, PM$_{2.5}$ pollution was higher in Lagos than in Hong Kong. They also found that vehicular emissions contributed the most to PM$_{2.5}$ pollution.

Aliphatic hydrocarbon compounds have been used in other parts of the world to identify the main sources of PM$_{2.5}$ pollution and to understand the important impact of regional transport on the characterisation of PM$_{2.5}$ (Andreou et al., 2007; Javed et al., 2019; Sun et al., 2021). For instance, Andreou et al. (2007) investigated the organic chemical composition of PM$_{2.5}$ in Athens to determine the emission sources. They found that all samples in Athens contained n-alkanes, biomarkers for fossil fuels, and a mixed origin (petrogenic and biogenic) of Athenian PM$_{2.5}$. Vehicular emissions were the main source of aliphatic hydrocarbon compounds, with biogenic sources contributing less. Recently, Sun et al. (2021) determined the sources of PM$_{2.5}$-associated PAHs and n-alkanes in Changzhou, China. Their results showed that biogenic sources are the main source of n-alkanes and PAHs in PM$_{2.5}$. The authors also observed that variations in the concentration of n-alkanes and PAHs from different air mass transports were not consistent with the changes in PM$_{2.5}$ mass, and concluded that regional transport has important effects on the characterisation of PM$_{2.5}$. This study therefore aimed at determining the PM$_{2.5}$ mass concentration and characterising the chemical composition of PM$_{2.5}$ collected at a residential location in Agege area of Lagos, Nigeria. The chemical analysis included the elemental carbon (EC), organic carbon (OC), aliphatic hydrocarbon compounds comprising of n-alkanes, hopanes and steranes. The impact of local and regional air mass transports on the amount of PM$_{2.5}$, elemental carbon (EC), organic carbon (OC), and aliphatic hydrocarbon compounds arriving at the study site was also assessed using the air mass trajectory analysis. In addition, the sources of PM$_{2.5}$ pollution were identified based on the molecular diagnostic indices of n-alkanes, hopanes and steranes profiles. It is expected that this work will provide useful information on the characteristic nature of PM$_{2.5}$ and in particular the sources and profiles of aliphatic hydrocarbons in PM$_{2.5}$ in residential areas of Lagos, which is currently scarce.

Materials and methods

Description of sampling site
The sampling site was an urban residential area located at 3/5 Morenike Carena Close, Orile Agege, Lagos (6.635008N and 3.302543E). The site was located within the city, and thus the anthropogenic emissions from various sources was quite high. Lagos is the former administrative capital of Nigeria, and the biggest metropolis in West Africa with a population of over 21 million (Alani et al., 2019). It remains the economic and industrial hub of the nation, where a range of activities are taking place that might be detrimental to the city's air quality. Lagos is susceptible to particulate matter pollution arising from vehicular traffic, diesel and gasoline generator emissions, open dumpsites, illegal waste burning, infrastructure construction, and household cooking using polluting fuel and stoves (Ibitayo 2012; Oseni 2016; Adegboye 2018; Adam 2018; Ozoh et al., 2018).

Sample collection
Thirty-six (36) PM$_{2.5}$ samples (24-h samples) and blank samples (4) were taken between June and July 2021 during the peak of the rainy season to provide an overview of the extent of the impact of the rainy season on the PM$_{2.5}$ mass concentrations and aliphatic hydrocarbon compounds characteristics in PM$_{2.5}$. Samples were collected on high-purity quartz fibre filters (Φ = 47 mm) using a low-vol "Gent" stacked PM$_{2.5}$ air sampler (Maenhaut et al., 1994). The device was placed at a height of 4.65 m above the ground to minimise blockage of air parcels from surrounding buildings and was operated at a constant flow rate of 18 L/min. The samples were stored in a refrigerator at 5°C and subsequently cooled in a container packed with frozen ice packs and transported to TROPOS in Leipzig, Germany within 24 h. Upon arrival, the samples were stored in the freezer at -20 °C prior to laboratory analysis.

Gravimetric and organic/elemental carbon (OC/EC) analysis

The mass of the PM$_{2.5}$ samples were quantified using a microbalance (Mod. AT261 Delta Range, Mettler-Toledo) after being allowed to equilibrate in the weighing room for 72 h under a climate-controlled conditions (temperature: 20 ± 1 °C and relative humidity: 50 ± 5%) before and after sampling. To determine the mass concentration, the weight difference of the filters before and after sampling was computed and divided by total sampling volume. Organic carbon and elemental carbon were analysed using a thermo-optical method (Sunset Laboratory Inc., USA) at a maximum temperature of 850 °C using the normalised temperature programme EUSAAR2 (EUropean Supersites for Atmospheric Aerosol Research) as described in the literature (Cavalli et al., 2010; Yttri et al., 2019). The method is in accordance with the standard proposed by the European networks (ACTRIS, EMEP). Samples were thermally desorbed from the filter medium under an inert He atmosphere followed by an oxidising O$_2$-He atmosphere, under carefully controlled heating ramps. A flame ionisation detector was used to quantify methane after catalytic methanation of CO$_2$. With the EUSAAR2 protocol, different OC fractions in an inert atmosphere (He) were measured at 200°C for 120s, at 300°C for 150s, at 450°C for 180s and at 650°C for 180s. Subsequently, the EC fractions were measured in an oxidising atmosphere (O$_2$-He) at 500°C for 120s, at 550°C for 120s, at 700°C for 70s and at 850°C for 80s (Cavalli et al., 2010). Lower OC/EC ratios are usually the result of charring processes' tendency to overestimate the EC and underestimate the OC. In order to adjust for the charring process, an optical correction was used. A laser with a wavelength of 678 nm was used to measure the sample's transmission in order to calculate the optical correction for charring for pyrolytic carbon. For OC and EC measurements, the detection threshold was 0.2 μg cm^{-2}.

Turpin and Lim (2001) evaluated organic matter (OM) using the conversion factor ƒOM/OC. The organic matter was around twice as much as the organic carbon (OM = 2.1 × OC). Because the conversion factor varies depending on the specific conditions at each site, the factor ƒOM/OC = 2.1 is recommended as it also takes the age of the aerosol into account (Turpin and Lim, 2001). Thus, the OM in the present study was estimated accordingly. The POC content can be estimated using EC as a tracer by multiplying the minimum OC/EC ratio determined for the entire study period by the EC content as follows (Huang et al., 2012; Deabji et al., 2021):

$$POC = (OC/EC)_{min} \times EC \qquad (1)$$

Consequently, the amount of SOC that contributes to total organic carbon can be determined as the difference between the concentrations of primary and secondary organic carbon using the following equation (Huang et al., 2012; Deabji et al., 2021):

$$SOC = OC - POC \qquad (2)$$

Organic compounds analysis

The analysis of aliphatic hydrocarbon compounds such as n-alkanes (C$_{20}$-C$_{34}$), hopanes, and steranes were carried out using a Curie-point pyrolyser (JPS-350, JAI Inc., Japan) coupled to a gas chromatography-mass spectrometry system (6890 N GC, 5973 inert MSD, Agilent Technologies, CA, USA). A detailed description of the analytical procedures has been previously documented (Neusüss et al. 2000). Briefly, filter aliquots were spiked with a solution of internal standards, including perdeuterated tetracosane-d$_{50}$ (C$_{24}$-D$_{50}$) and dotriacontane-d$_{66}$ (C$_{32}$-D$_{66}$). Two circular filter punches (6 mm; 56.5 mm^2) from each sample were then coated with an alloy of iron and nickel (50% Fe; 50% Ni) and immediately evaporated in a pyrolysis chamber at 510 °C for 4 s in a helium environment. The compounds were separated using a capillary column coated with a stationary phase of 5 % phenyl-arylene and 95 % dimethylpolysiloxane (ZB-5MS, 30 m × 0.25 mm i.d. × 0.25 μm film thickness). The GC and MS conditions had been previously described by Khedidji et al. (2020). Individual compounds were identified by comparing the mass spectra with literature and library data and validated with standard compounds. Internal calibration was performed using the respective internal standards. The GC-MS data were acquired using dedicated software (ChemStation) from Agilent. For each compound analysed, the sample concentration was calculated by subtracting the average concentration of the blank filter from the measured concentration in the sample.

Molecular diagnostic ratios

To investigate the origin of the n-alkanes in the PM$_{2.5}$ samples, the following diagnostic ratios were used.

The carbon preference index (CPI): CPI is a diagnostic technique that depicts the relationship of proportionality between alkanes with odd and even carbon chains in a given sample. Based on several studies (Bray and Evans, 1961; Simoneit et al.,1991; Boreddy et al., 2018), the CPI for n-alkanes (odd to even ratio) in the PM$_{2.5}$ was calculated as follows:

$$CPI = \frac{\sum odd\ (C21 - C33)}{\sum even\ (C20 - C34)} \qquad (3)$$

The average chain length (ACL): ACL is based on the prevalence of odd high homologs. It is estimated as the mean number of carbon atoms per molecule (Caumo et al., 2020). ACL has been used to identify the origins of n-alkanes in a given sample (Kawamura et al., 2003; Boreddy et al., 2018; Caumo et al., 2020), and based on these studies, the ACL for n-alkanes in PM$_{2.5}$ was obtained according to the following equation:

$$ACL = \frac{[25(C25) + 27(C27) + 29(C29) + 31(C31) + 33(C33)]}{[C25 + C27 + C29 + C31 + C33]} \qquad (4)$$

Odd-even predominance (OEP): The odd-even computation also known as the odd-even carbon number by dividing the concentration of odd-numbered n-alkanes by the concentration of even-numbered n-alkanes as follows:

$$OEP = \frac{C21 + 6(C23) + C25}{4(C22 + C24)} \qquad (5)$$

Air mass back trajectory

96-hour air mass back trajectories for each sample collection time interval were determined using the HYSPLIT model version 5 (www.ready.noaa.gov/HYSPLIT_traj.php, last use February 2023, Stein et al., 2015) to evaluate the origin of the PM$_{2.5}$ during the sampling period. The choice of using 96-h was to provide a representation for fine mode particles (PM$_{2.5}$) that have longer atmospheric lifetimes as coarse mode particles. The Global Data Assimilation System meteorological data set was used for the HYSPLIT trajectory calculations with a 1°-degree grid size. The obtained trajectories were further processed using the r studio software open-air package (https://davidcarslaw.github.io/openair) for graphical presentation. The computed trajectories also contained information of the air mass history, its residence time (average time the air parcel stays over a given grid cell or geographical landscape during its transport prior to arrival at the receptor site) over given geographical landscapes, different mixing depts (height at which the potential temperature of the air mass starts to change), radiation and general meteorology information that the air mass experienced during its transport. Using the trajCluster function of the open-air r package, a cluster analysis of the total determined trajectories was performed. Here, the trajectories were grouped according to the least Euclidian distance between the trajectory's points. After several iterations amongst pairs of trajectories, the average trajectory representative of the minimum distance between the trajectories with a low total spatial variance (TSV) was determined and assigned as a cluster. The equation applied to determine the Euclidian distance (d (1,2)) between two points of two trajectories 1 and 2 at positions (X1, Y1) and (X2, Y2) respectively, is given as (Stein et al., 2015):

$$d_{1,2} = \left(\sum_{i=1}^{n} \left((X_{1i} - X_{2i})^2 + (Y_{1i} - Y_{2i}) \right)^2 \right)^{1/2} \quad (6)$$

The selection of the final number of clusters involves a mathematical process wherein the total spatial variance is compared with the model estimated number of clusters. The level at which a change in the number of clusters significantly increases the TSV is considered as the point of the optimum number of clusters for the total evaluated back trajectories. In this study, 5-cluster solution provided a reasonable spatial representation of the entire computed trajectories and was considered the best solution of this analysis. The clusters were labelled C1 to C5 and were assigned to each sample. The samples chemical composition including their PM$_{2.5}$ mass was averaged according to their respective clusters and the relative contributions of the clusters to the chemical components were evaluated.

Results and discussion

PM$_{2.5}$ mass concentration and its carbonaceous components

Table 1 summarises the 24-h average PM$_{2.5}$ mass concentrations and its carbonaceous chemical components for the sampling period (June to July 2021). The 24-h PM$_{2.5}$ mass concentrations ranged from 8.7 to 56.5 µg m^{-3} (avg. 27 ± 11.1 µg m^{-3}), surpassing the daily threshold of 15 µg m^{-3} recommended by World Health Organisation (WHO, 2021). The OC concentration ranged from 1.0 to 4.9 µg m^{-3} (avg. 2.2 ± 1.0 µg m^{-3}). On average, OC accounted for 8% of the total PM$_{2.5}$ mass and contributed 73% of the carbonaceous aerosol while the majority of OC consisted of POC (68%), indicating that the OC was a crucial component of PM$_{2.5}$ and the primary emission sources of OC in the study area need to be controlled. The EC concentration ranged from 0.4 to 1.8 µg m^{-3} (avg. 0.8 ± 0.3 µg m^{-3}). On average, EC constituted about 3% of the total PM$_{2.5}$ mass. Though this value could be viewed as only a small portion of ambient PM$_{2.5}$, EC has been recognised as a crucial sign of unfavourable health impacts (Janssen et al., 2011). With a correlation value of r^2 = 0.81 (Fig. 1a), OC and EC demonstrate a strong relationship, indicating that the majority of the OC at the site was produced as a primary aerosol with EC. This revealed that EC and OC, as well as the precursor that resulted in SOC formation, could have an identical source. The positive bi-modal correlation (r^2 = 0.76 and 0.40) between SOC and EC indicated that the primary combustion sources have an influence on the generation of SOC (Fig. 1b), and also suggested two distinct associations such as sources or atmospheric processes linking the two different carbonaceous components. The OC/EC ratios ranged from 2 to 5.1 µg m^{-3} (avg. 2.9 ± 0.7 µg m^{-3}). Hildemann et al. (1991), reported 2.2 µg m^{-3} for light-duty gasoline vehicles while Cao et al. (2005) observed 4.1 µg m^{-3} for vehicle exhaust. This suggested that the most probable common source of PM$_{2.5}$ emission in the area was gasoline-powered engines. Generally, OC/EC ratio > 2 is an indicator of SOC formation in the atmosphere (Javed et al., 2019).

Table 1: *Summary of 24-h average PM$_{2.5}$, and carbonaceous constituents (µg m^3) in Lagos, Nigeria*

	Minimum	Maximum	Average	Standard deviation
PM$_{2.5}$ mass	8.7	56.5	27.0	11.1
EC	0.4	1.8	0.8	0.3
OC	1.0	4.9	2.2	1.0
OC/EC	2.0	5.1	2.9	0.7
POC	0.8	3.7	1.5	0.7
SOC	0.0	1.7	0.6	0.5
OM	2.2	10.3	4.5	2.1

n-alkanes in PM$_{2.5}$

The concentrations of aliphatic hydrocarbons detected in the PM$_{2.5}$ samples from the residential area in Lagos and the molecular diagnostic indices are presented in Table 2. The aliphatic fraction of the PM$_{2.5}$ was dominated by n-alkanes from C$_{20}$ to C$_{34}$, and maximizing at C$_{25}$, followed by C$_{26}$ and C$_{20}$, respectively (Fig. 2). The total concentrations of the n-alkanes $\sum$(C$_{20}$-C$_{34}$) in the samples ranged from 1.8 to 146.6 ng m^{-3} (avg. 43.6 ± 35.1 ng m^{-3}) (Table 2). On average, n-alkane contributed 0.2% and 1.0% of the total PM$_{2.5}$ mass and OM budget,
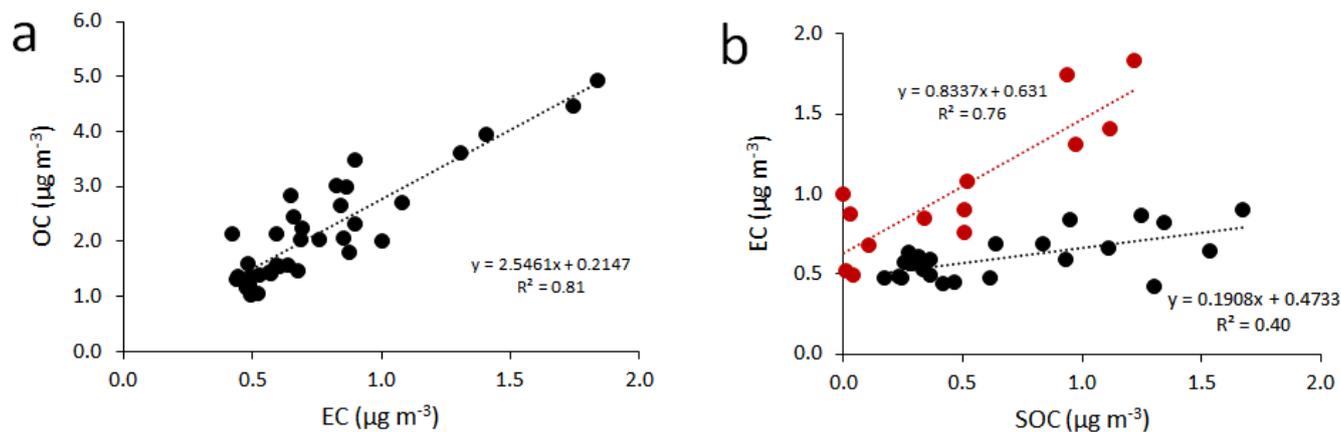
Figure 1: *(a, left) Plot of OC versus EC, and (b, right) EC versus SOC showing the relationship between the parameters. Samples with the same colour indicate a similar association (source or atmospheric processes).*

Table 2: *Aliphatic hydrocarbon concentrations (ng m^{-3}) and molecular indices of n-alkanes in PM$_{2.5}$ from a residential area in Lagos, Nigeria*

Compound	Minimum	Maximum	Average	Standard deviation
∑n-alkanes (C$_{20}$-C$_{34}$)	1.8	146.6	43.6	35.1
Indices				
CPI	0.0	2.3	0.7	0.5
ACL	25.0	30.8	25.7	1.6
OEP	0.0	1.9	0.5	0.5
Hopanes				
17α(H), 21β(H)-30-Norhopane	0.0	22.1	4.4	7.0
17α(H), 21β(H)-Hopane	0.0	31.7	5.6	8.9
17α(H), 21β(H)-22S-Homohopane	0.0	89.9	2.9	15.1
17α (H), 21β(H)-22R-Homohopane	0.0	14.1	1.9	3.7
∑$_4$Hopanes	0.0	89.9	18.7	25.9
Steranes				
α, α, α 20R-Cholestane	0.0	3.1	0.3	0.8
α, β, β (20R 24S)-24-Ethylcholestane	0.0	15.1	1.7	3.9
α, α, α (20R 24S)-24-Ethylcholestane	0.0	7.9	1.3	2.1
∑$_3$Steranes	0.0	26.0	3.3	6.7

respectively, indicating a sizeable portion of the ambient PM$_{2.5}$ and organic matter concentration in the area. A comparable range of total n-alkanes concentrations in PM$_{2.5}$ were recently found in densely populated and traffic-intensive city of Beijing, China (4.51-153 ng m^{-3}) (Yang et al., 2023), but higher than the average total concentrations recorded in PM$_{2.5}$ in a residential/commercial area in Doha, Qatar (8.04 ± 7.74 ng m^{-3}) (Javed et al., 2019), an urban residential area (Aglantizia) in Nicosia, Cyprus (13 ± 12 ng m^{-3}) (Iakovides et al., 2021), and roadsides in Lisbon, Portugal (22.4 ± 17.9 ng m^{-3} in winter and 23.3 ± 2.83 ng m^{-3} in summer) (Alves et al., 2016). In contrast, the average total concentration of n-alkanes obtained in this work was lower than some urban cities in China (Changzhou: 252.37 ± 184.02 ng m^{-3}; Nanjing: 205 ng m^{-3}; Changchun: 209 ng m^{-3}; Shanghai: 259 ng m^{-3} in PM$_{2.5}$) (Wang et al., 2006; Haque et al., 2019; Sun et al., 2021) and Hong Kong (195 ng m^{-3}) (Wang et al., 2006). The prevalence of low carbon number (C$_{20}$-C$_{26}$) in the aerosol particles showed a predominance of anthropogenic sources, such as incomplete combustion of fossil fuels (Zhang et al., 2018). Fossil fuel-derived n-alkanes with the dominant of C$_{25}$ and C$_{20}$ homologs are considered to be from gasoline engines while C$_{20}$-dominated n-alkanes are regarded as from heavy and medium-duty diesel engines (Rogge et al., 1993; Schauer et al., 1999). The preponderance of C$_{25}$ and C$_{20}$ in the samples (Fig. 2) showed that anthropogenic emissions resulting from gasoline and diesel engines were probably the dominant sources of n-alkanes in the area under study.

The carbon preference index (CPI) values calculated from n-alkane distribution have been extensively employed as
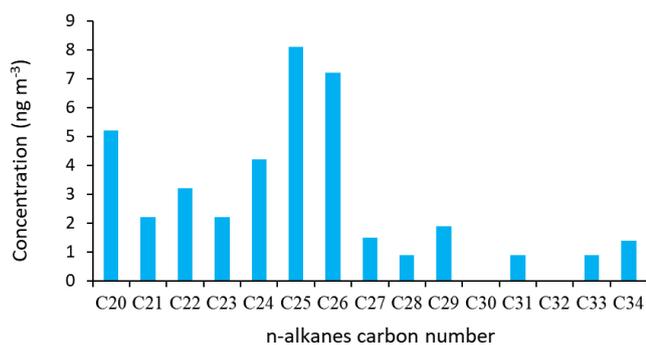
Figure 2: Average concentrations of n-alkanes in the PM$_{2.5}$ samples.

a source marker in aerosol samples (Simoneit et al., 1991; Andreous et al., 2008; Alves, 2008; Alves et al., 2016; Boreddy et al., 2018; Sun et al., 2021). The CPI values obtained from n-alkane distribution ranged from 0.0 to 2.3 (avg. 0.7 ± 0.5) (Table 2). CPI values close to 1 were attributed to pollution from petrogenic sources, while values above 3 were attributed to biogenic sources (Omar et al., 2007; Alves, 2008). Based on the average CPI value determined in this work, the n-alkanes in PM$_{2.5}$ originated mainly from a petrogenic source. The ACL has also been effectively used to pinpoint aerosol pollution sources (Boreddy et al., 2018; Caumo et al., 2020). The ACL index for n-alkanes in the present PM$_{2.5}$ samples ranged from 25.0 to 30.8 (avg. 25.7 ± 1.6) (Table 2); the wide variation in the index suggested that the primary source of n-alkanes in PM$_{2.5}$ stemmed from petrogenic contamination (Jeng, 2006). The OEP is an efficient tool that can give details about the various n-alkane sources (Ladji et al., 2009). The OEP results computed from the n-alkanes in the PM$_{2.5}$ samples ranged from 0.0 to 1.9 (avg. 0.5 ± 0.5) (Table 2). In general, OEP values of less than 1.3 are attributed to contamination by crude oil (Scalan and Smith, 1970). The low average OEP value suggested aerosol pollution arising from petroleum sources (Scalan and Smith, 1970; Sojinu et al., 2012).

Hopanes and steranes in PM$_{2.5}$

The concentrations of hopanes and steranes detected in the PM$_{2.5}$ samples during the entire campaign period are listed in Table 2. Four (4) hopanes including 17α(H),21β(H)-30-norhopane, 17α(H),21β(H)-hopane, 17α(H),21β(H)-22S-homohopane, and 17α(H),21β(H)-22R-homohopane and three (3) steranes including α, α, α 20R-Cholestane, α, β, β (20R 24S)-24-Ethylcholestane and α, α, α (20R 24S)-24-Ethylcholestane, were detected in the PM$_{2.5}$ samples (Table 2). The total concentrations of hopanes (Σ4 hopanes) and steranes (Σ3 steranes) varied from 0.0 to 89.9 ng m^{-3} (avg. 18.7 ± 25.9 ng m^{-3}) and 0.0 to 26.0 ng m^{-3} (avg. 3.3 ± 6.7 ng m^{-3}), respectively, in PM$_{2.5}$. On average, hopanes accounted for 0.1% and 0.4% of the total PM$_{2.5}$ and OM, while steranes contributed 0.01% and 0.1% of the total PM$_{2.5}$ and OM, respectively, making them a non-negligible part of the organic matter content in the study area. The average total hopanes and steranes concentrations in this study were higher than those reported in PM$_{2.5}$ in a residential/commercial area in Doha, Qatar (0.521 ± 0.677 ng m^{-3}) and (0.162 ± 0.25 ng m^{-3}), respectively (Javed et al., 2019). Similarly, lower

average hopanes and steranes concentrations were observed in an urban residential area in Nicosia, Cyprus (0.83 ± 1.04 ng m^{-3}) and (0.27 ± 0.39 ng m^{-3}), respectively. The average hopanes level in this study was likewise higher than those observed in roadsides areas in Lisbon, Portugal in winter (1.71 ± 1.55 ng m^{-3}), but comparable to those observed in roadside areas in Lisbon, Portugal in summer (3.23 ± 1.15 ng m^{-3}) (Alves et al., 2016). The presence of hopanes and steranes in PM$_{2.5}$ samples suggested fossil fuels combustion in the area (Simoneit et al., 2004; Javed et al., 2019). The steranes were dominated by α, β, β (20R 24S)-24-Ethylcholestane (Table 2). The stereochemical configurations at the C17 and C21 positions of hopanes are frequently used to assess the thermal maturity levels of fossil fuels, and have proved useful in evaluating the source of hopanes in aerosol studies (Simoneit et al., 2004; Barakat, 2002; Mikuška, Křůmal, and Večeřa 2015; Javed et al., 2019). Hopanes with configurations of 17β(H), 21β(H) are considered immature; 17β(H), 21α(H) are of low maturity while 17α(H), 21β(H) are fully mature (Mikuška, Křůmal, and Večeřa 2015; Javed et al., 2019). The main homologs of hopanes detected in the samples were the thermodynamically more stable 17α(H), 21β(H) configurations, with a preponderance of the 17α(H), 21β(H)-hopane compound (C30αβ; 36% of total hopanes). This was followed by 17α(H), 21β(H)-norhopane (C29αβ; 28%) (Fig. 3), a fingerprint for vehicle emissions (Mikuška, Křůmal, and Večeřa 2015; Javed et al., 2019). The dominance of αβ configuration indicated that atmospheric contamination in the study area emanated from matured petroleum. Again, the higher concentration of the 22S hopane relative to the corresponding 22R epimer (Table 2; Fig. 3), further supported the fact that the hopanes were primarily derived from gasoline and diesel engine exhaust (Rushdi et al. 2017; Javed et al., 2019). The enhanced levels of these petroleum biomarkers (Barakat, 2002; Mikuška, Křůmal, and Večeřa 2015; Javed et al., 2019), indicated a significant impact of petrogenic source emission in the study area.
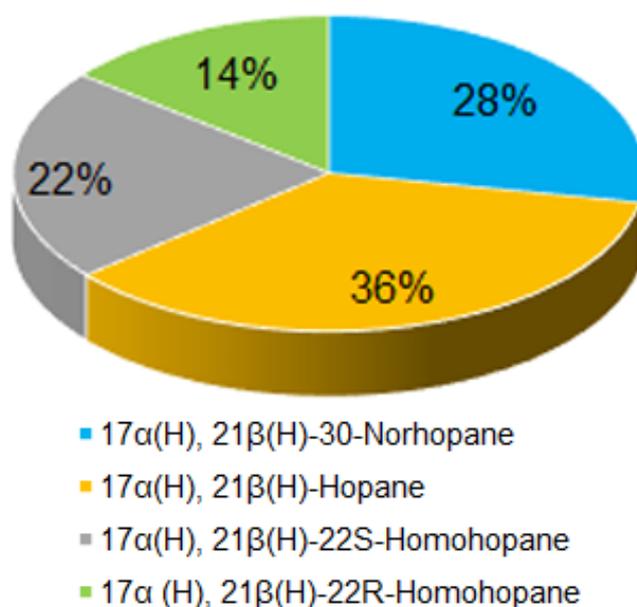
Figure 3: The percentage composition of hopanes in the PM$_{2.5}$.
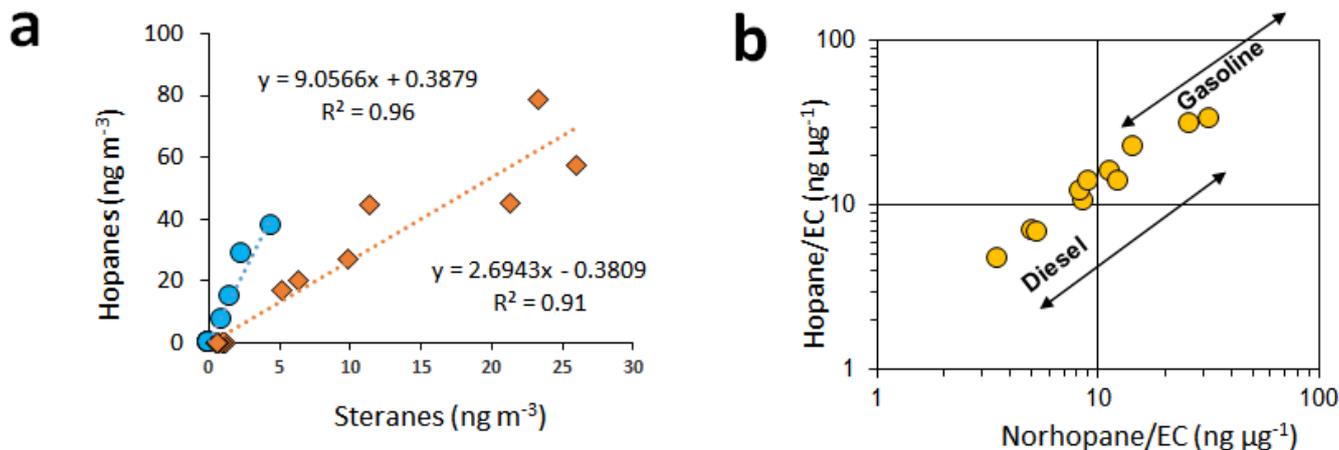
Figure 4: *(a, left) Cross plot of hopanes versus steranes. Samples with the same colour indicate a similar association (source or atmospheric processes) between hopanes and steranes in Fig. 4a, and (b, right) Ratio-ratio plot of hopane and norhopane normalised by EC (Modified after Yu et al., 2011).*

Figure 5: *96-hours backward air mass trajectories arriving at the sampling site during the sampling period in the rainy season.*

44% and 25%, respectively, of the total air mass inflow during the sampling period and were characterised by their different origins, but with a similar profile in the mixing depth and trajectory heights (air masses altitudes) close to their arrival at the sampling site. C3 (13%) and C4 (15%) were representative of air masses that spent more time over the Atlantic Ocean and little time over terrain with C4 passing closer to the coast of neighbouring Benin republic while C3 was confined within the coast of Nigeria and originated from the Gulf of Guinea region. C5 made up only about 2% of the trajectories but represented air masses originating from the coastal area of Nigeria with higher residence time over land and vegetation regions with low mixing depth. These characteristics made it contributed significantly to the composition of the particles at the sampling site.

Influence of source regions on PM$_{2.5}$ mass and carbonaceous components

Fig. 6 gives the quantified contributions of the different directions of air masses to the PM$_{2.5}$ mass and its carbonaceous components. Interestingly, air mass for cluster 5 (C5) with few episodes of air transports contributed more to PM$_{2.5}$ mass (22%), EC (21.4%), OC (24.7%), OC/EC (23%), POC (21.4%), SOC (32%), and OM (24.7%) (Fig. 6a), as compared to air masses for clusters 1 to 4 (C1 to C4) which passed mainly through the Atlantic Ocean before crossing the mainland to the sampling site. Cluster 5 after emerging from the sea has a relatively long residence time in the continental coastal areas of the Atlantic Ocean before returning to the marine area and eventually crossing the mainland to the sampling site. The relatively low mixing depth of the air mass, high exposure to different continental environments and natural vegetation during transports may have raised the levels of the PM$_{2.5}$ mass and its chemical components in the C5 trajectory (Fig. 6b).

Two strong positive correlations (r^2 = 0.96 and 0.90) were observed between hopanes and steranes (Fig. 4a), indicating two separate associations such as sources or atmospheric processes linking the two different types of compounds. Hopanes and EC have been used to allocate gasoline and diesel emissions (Yu et al., 2011). Diesel engines are strong contributors to both EC and hopanes, whereas gasoline engines are huge sources of hopanes but only contribute moderate amounts of EC. As a result, diesel-powered engines have substantially lower hopanes to EC ratios than engines that run on gasoline (Yu et al., 2011). The ratio-ratio plot of hopane (17α(H),21β(H)-hopane) and norhopane (17α(H),21β(H)-30-norhopane) obtained for PM$_{2.5}$ in this study, normalised by EC is shown in Fig. 4b, modified from Yu et al. (2011). The plot corroborated the sources of hopanes as being from diesel and gasoline engines due to the strong correlation between the groups of compounds, which might have emanated from vehicle emissions, motorbikes, and fumes emitted by diesel and gasoline engines.

Air mass source regions

As shown in Fig. 5, air masses originated from different regions of the Atlantic Ocean crossing through various densely populated areas in the coastal settlements in Lagos at different altitudes before arriving at the site. The clusters C1 and C2, represent

Influence of source regions on aliphatic hydrocarbon compounds

The contributions of the different direction of air mass to aliphatic hydrocarbon compounds are shown in Fig. 6. As previously observed in the carbonaceous materials and PM$_{2.5}$ mass
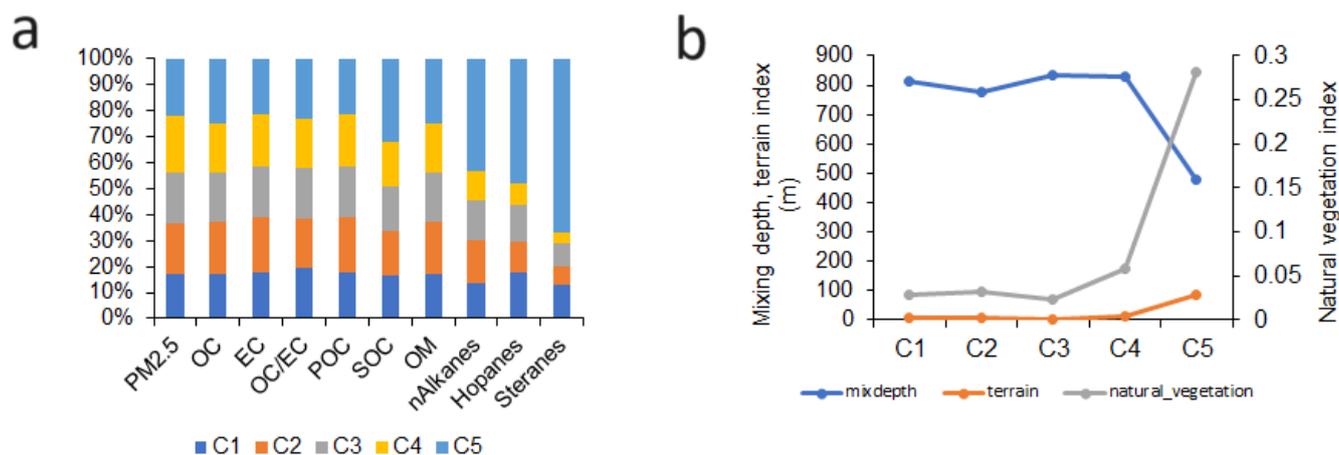
Figure 6: *(a, left) Plot showing the various contributions of different clusters to PM$_{2.5}$ mass concentration, its carbonaceous components, and aliphatic hydrocarbons, (b, right) Plot showing the average mixing depth, terrain, and natural vegetation of the air mass trajectories.*

concentrations, cluster C5 with few episodes also contributed significantly to the budgets of the aliphatic hydrocarbon compound classes as compared to the other clusters. C5 air mass contributed 70%, 50%, and 43% of steranes, hopanes, and n-alkanes concentrations in this region, respectively. The contributions of C1 and C3 were almost similar for the three classes ranged between 12% and 18% for C1 and 9% to 15% for C3. This was likely due to the similar trajectory routes the air masses experienced before arriving at the sampling site. C4 contributed the least to the aliphatic compounds with relative contributions ranged from 3% to 6% for steranes and n-alkanes, respectively. High impact of steranes by long distant transport (e.g., C5) indicated the stability of these compounds in the atmosphere. The differences in the cluster contributions and the stronger dominance of the C5 air mass can be ascribed to the relatively low mixing depth of the air mass, less residence time over the ocean, and high exposure to different continental environments as well as natural vegetation during the air mass transport in comparison to the C1 to C4 clusters. It was also interesting to observe the similar contribution of C1 across the components, indicating a constant influence of local sources in this air mass trajectory. Transport over continental and vegetated regions allowed local emissions to interact with the transported air masses, resulting in enhanced levels of these compounds in such air mass trajectories.

Conclusion

The total concentrations of ∑n-alkanes (C$_{20}$-C$_{34}$), hopanes (∑$_4$Hopanes), and steranes (∑$_3$Steranes) determined from PM$_{2.5}$ samples collected from a residential area of Lagos ranged from 1.8 to 146.6 ng m^{-3}, 0.0 to 89.9 ng m^{-3}, and 0.0 to 26.0 ng m^{-3}, amounting to 0.2%, 0.1%, and 0.01% of the total PM$_{2.5}$ mass concentrations, and 1%, 0.4% and 0.1% of the organic matter contents, respectively. N-alkanes diagnostic indices, hopanes, and steranes profiles showed that gasoline and diesel engines were the major contributors to particulate matter pollution in the studied area. Therefore, controlling gasoline and diesel emission sources are key steps to minimising air pollution

in the area. Based on the air mass trajectories, the levels of PM$_{2.5}$, carbonaceous materials, and aliphatic hydrocarbon compounds arriving at the study site have been considerably impacted by both local and regional air transports. This study could help decision-makers and environmental stakeholders to develop specific, focused, and efficient management strategies for mitigating local air pollution challenges in Lagos, Nigeria.

Author contribution

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References

Adama O, 2018, 'Urban Imaginaries: Funding Mega Infrastructure Projects in Lagos, Nigeria', GeoJournal, 83, 2, 257-274, doi. org/10.1007/s10708- 016-9761-8.

Adegboye K, 2018, "Why Problem of Waste Management Persists in Lagos." Vanguard. https://www.vanguardngr.com/2018/10/why-problem-of-waste-management-persists-in-lagos-stakeholders/.

Alani R.A, Ayejuyo O.O, Akinrinade O.E, Badmus G.O, Festus C.J, Ogunnaike B.A, Alo B.I, 2019, 'The level PM$_{2.5}$ and the elemental compositions of some potential receptor locations in Lagos, Nigeria', Air Quality, Atmosphere and Health, 12,1251-1258, doi.org/10.1007/s11869-019-00743-3.

Alves C.A, 2008, 'Characterisation of solvent extractable organic constituents in atmospheric particulate matter: An overview', Anais da Academia Brasileira de Ciências, 80, 21-82.

Alves C.A, Oliveira C, Martins N, Mirante F, Caseiro A, Pio C, Matos M, Silva H.F, Oliveira C, Camões F, 2016, 'Road tunnel, roadside, and urban background measurements of aliphatic compounds in size-segregated particulate matter', Atmospheric Research, 168:139-148, doi.org/10.1016/j.atmosres.2015.09.007.

Andreou G, Alexiou S.D, Loupa G, Rapsomanikis S, 2008, 'Identification, Abundance and Origin of Aliphatic Hydrocarbons in the Fine Atmospheric Particulate Matter of Athens', Greece, Water, Air, and Soil Pollution: Focus, 8, 99-106, doi.org/10.1007/s11267-007-9142-x.

Barakat A.O, 2002, 'PAHs and petroleum markers in the atmospheric environment of Alexandria City, Egypt' Water, Air, and Soil Pollution 139, 289-310, doi.org/10.1023/A:1015894520672.

Boreddy S.K.R, Haque M.M, Kawamura K, Fu P, Kim, Y, 2018, 'Homologous series of n-alkanes (C$_{19}$-C$_{35}$), fatty acids (C$_{12}$-C$_{32}$) and alcohols (C$_8$-C$_{30}$) in atmospheric aerosols from central Alaska: Molecular distribution, seasonality and source indices', Atmospheric Environment, 184, 87-97, doi.org/10.1016/j.atmosenv.2018.04.021.

Bray E.E, Evans E.D, 1961, 'Distribution of n-paraffins as a clue to recognition of source beds', Geochimica Cosmochimica, Acta 22, 2-15, doi.org/10.1016/0016-7037(61)90069-2.

Brown S.G, Herckes P, Ashbaugh L, Hannigan M.P, Kreidenweis S.M, Collett J.L, 2002, 'Characterization of organic aerosol in Big Bend National Park, Texas', Atmospheric Environment, 36, 5807-5818. doi.org/10.1016/S1352-2310(02)00578-2.

Cao J.J, Wu F, Chow J.C, Lee S.C, Li Y, Chen S.W, An Z.S, Fung K.K, Watson J.G, Zhu C.S, Liu S.X, 2005, 'Characterization and source apportionment of atmospheric organic and elemental carbon during fall and winter of 2003 in Xi'an, China', Atmospheric Chemistry and Physics, 5, 3127-37. doi.org/10.5194/acp-5-3127-2005.

Caumo S, Bruns R.E, Vasconcellos P.C, 2020, 'Variation of the Distribution of Atmospheric n-Alkanes Emitted by Different Fuels' Combustion', Atmosphere, 11, 643, doi:10.3390/atmos11060643.

Cavalli F, Viana M, Yttri K.E, Genberg J, Putaud J.P, 2010, 'Toward a standardised thermal-optical protocol for measuring atmospheric organic and elemental carbon: the EUSAAR protocol' Atmospheric Measurement Techniques, 3, 1, 79–89, doi.org/10.5194/amt-3-79-2010.

Deabji N, Fomba K.W, El Hajjaji S, Mellouki A, Poulain L, Zeppenfeld S, Herrmann H, 2021, 'First insights into northern Africa high-altitude background aerosol chemical composition and source influences', Atmospheric Chemistry and Physics, 21, 18147-18174, doi.org/10.5194/acp-21-18147-2021.

Ezeh, G.C. Obioh I.B, Asubiojo O.I, Chiari M, Nava S, Calzolai G, Lucarelli F, Nuviadenu C.K., 2014, 'Elemental compositions of PM$_{10-2.5}$ and PM$_{2.5}$ aerosols of a Nigerian urban city using ion beam analytical techniques', Nuclear Instruments and Methods in Physics Research B, 334, 28-33, doi.org/10.1016/j.nimb.2014.04.022.

Ezeh G.C, Obioh I.B, Asubiojo O.I, Onwudiegwu C.A, Nuviadenu C. K, Ayinla S.A, 2018, 'Airborne fine particulate matter (PM$_{2.5}$) at industrial, high- and low-density residential sites in a Nigerian megacity', Toxicological and Environmental Chemistry, 100, 3, 326-333, doi.org/10.1080/02772248.2018.1485924.

Ezeh G. C, Obioh I.B, Asubiojo O.I, Abiye O.E, 2012, 'PIXE characterization of PM$_{10}$ and PM$_{2.5}$ particulates sizes collected in Ikoyi Lagos, Nigeria', Toxicological and Environmental Chemistry, 94, 5, 884-894,doi.org/10.1080/02772248.2012.674133.

Fu P, Kawamura K, Okuzawa K, Aggarwal S.G, Wang G, Kanaya Y, Wang Z, 2008, 'Organic molecular compositions and temporal variations of summertime mountain aerosols over Mt. Tai, North China Plain', Journal of Geophysical Research: Atmospheres, 113, D19107. doi.org/10.1029/2008JD009900.

Gupta S, Gadi R, Mandal T.K, Sharma S.K, 2017, 'Seasonal variations and source profile of n-alkanes in particulate matter (PM$_{10}$) at a heavy traffic site, Delhi,' Environmental Monitoring and Assessment, 189: 43, doi.org/10.1007/s10661-016-5756-7.

Hildemann L.M, Markowski G.R, Cass G.R, 1991, 'Chemical Composition of Emissions from Urban Sources of Fine Organic Aerosol', Environmental Science and Technology, 25, 744-759, doi.org/10.1021/es00016a021.

Huang H, Ho K.F, Lee S.C, Tsang P.K, Ho, S.S.H, Zou C.W, Zou S.C, Cao J.J, Xu H.M, 2012, 'Characteristics of carbonaceous aerosol in PM$_{2.5}$: Pearl Delta River region, China', Atmosheric Research 104-105, 227–236, doi.org/10.1016/j.atmosres.2011.10.016.

Haque Md. M, Kawamura K, Deshmukh D.K, Fang C, Song W, Mengying B, Zhang Y-L, 2019, 'Characterization of organic aerosols from a Chinese megacity during winter: predominance of fossil fuel combustion', Atmospheric Chemistry and Physics, 19, 5147–5164, 2019, doi.org/10.5194/acp-19-5147-2019.

Iakovides M, Iakovides G, Stephanou E.G, 2021, 'Atmospheric particle-bound polycyclic aromatic hydrocarbons, n-alkanes, hopanes, steranes and trace metals: PM$_{2.5}$ source identification, individual and cumulative multi-pathway lifetime cancer risk assessment in the urban environment', Science of the Total Environment, 752, 141834, doi.org/10.1016/j.scitotenv.2020.141834.

Ibitayo O.O, 2012, 'Towards Effective Urban Transportation System in Lagos, Nigeria: Commuters' Opinions and Experiences', Transport Policy 24,141-147, doi.org/10.1016/j.tranpol.2012.07.009.

Janssen N.A.H, Hoek G, Simic-Lawson M, Fischer P, van Bree L, Brink H.T, Keuken M, Atkinson R.W, Anderson H.R, Brunekreef B, Cassee F.R, 2011, 'Black carbon as an additional indicator of the adverse health effects of airborne particles compared with PM$_{10}$ and PM$_{2.5}$,', Environmental Health Perspectives, 119, 1691-1699, doi.org/ 10.1289/ehp.1003369.

Javed W, Iakovides M, Euripides G.S, Wolfson J.M, Koutrakis P, Guo B, 2019, 'Concentrations of aliphatic and polycyclic aromatic hydrocarbons in ambient PM$_{2.5}$ and PM$_{10}$ particulates in Doha, Qatar', Journal of the air and waste management association, 62, 2, 162-177, doi.org/10.1080/10962247.2018.1520754.

Jeng W.-L, 2006, 'Higher plant n-alkane average chain length as an indicator of petrogenic hydrocarbon contamination in marine sediments', Marine Chemistry, 102, 242-251, doi.org/10.1016/j.marchem.2006.05.001.

Kawamura K, Ishimura Y, Yamazaki K, 2003, 'Four years' observations of terrestrial lipid class compounds in marine aerosols from the western North Pacific', Global Biogeochemical Cycles, 17, 1003, doi.org/10.1029/2001GB001810.

Khedidji S, Müller K, Rabhi L, Spindler, G, Fomba K.W, Pinxteren, D.V, Yassaa N, Herrmann H, 2020, 'Chemical Characterization of Marine Aerosols in a South Mediterranean Coastal Area Located in Bou Ismaïl, Algeria', Aerosol and Air Quality Research, 20, 2448–2473, doi.org/10.4209/aaqr.2019.09.0458.

Ladji R, Yassaa N, Balducci C, Cecinato A, Meklati B.Y, 2009, 'Annual variation of particulate organic compounds in PM$_{10}$ in the urban atmosphere of Algiers', Atmospheric Research, 92, 258-269, doi.org/10.1016/j.atmosres.2008.12.002.

Lyu Y, Xu T, Yang X, Chen J, Cheng T, Li X, 2017, 'Seasonal contributions to sizeresolved n alkanes (C8–C40) in the Shanghai atmosphere from regional anthropogenic activities and terrestrial plant waxes', Science of the Total Environment, 579, 19181928, doi.org/10.1016/j.scitotenv.2016.11.201.

Maenhaut W. Francois F, Cafmeyer J, 1994. 'The 'Gent' Stacked Filter Unit Sampler for the Collection of Atmospheric Aerosols in Two Size Fractions: Description and Instructions for Installation and Use. In Applied Research on Air Pollution using Nuclear-Related Technique', IAEA Report NAHRES, 19, 249-263, Vienna.

Mandalakis M, Tsapakis, M, Tsoga A, Stephanou, E. G, 2002, 'Gas-particle concentrations and distribution of aliphatic hydrocarbons, PAHs, PCBs and PCDD/Fs in the atmosphere of Athens (Greece)', Atmospheric Environment, 36, 25,4023–4035, doi.org/10.1016/S1352-310(02)00362-X.

Mikuška P, Křůmal K, Večeřa Z, 2015, 'Characterization of organic compounds in the PM$_{2.5}$ aerosols in winter in an industrial urban area', Atmospheric Environment, 105,97-108, doi: 10.1016/j.atmosenv.2015.01.028.

Mudge S.M, Duce C.E, 2005, 'Identifying the source, transport path and sinks of sewage derived organic matter', Environmental Pollution, 136,2, 209-220, doi: 10.1016/j.envpol.2005.01.015.

Neusüss C, Pelzing M, Plewka A, Herrmann H, 2000, 'A new analytical approach for size-resolved speciation of organic compounds in atmospheric aerosol particles: Methods and first results', Journal of Geophysical Research, 105, 4513-4527, doi.org/10.1029/1999JD901038.

Obioh I.B, Ezeh G.C, Abiye O.E, Alfa A, Ojo E.O, Ganiyu A.K, 2013, 'Atmospheric particulate matter in Nigerian megacities', Environmental Toxicology and Chemistry, 95, 3, 379-385. doi.org/10.1080/02772248. 2013.790970.

Omar N.Y.M.J, Bin Abas M.R, Rahman N.A, Tahir N.M, Rushdi A, Simoneit B.R.T, 2007, Levels and distribution of organic source tracers in air and roadside dust particles of Kuala Lumpur, Malaysia, Environmental Earth Sciences, 52, 1485-1500, doi.org/10.1007/s00254-006-0593-6.

Oseni M.O, 2016, 'Get Rid of It: To What Extent Might Improve Reliability Reduce Self-Generation in Nigeria?', Energy Policy, 93, 246-54, https://doi.org/10.1016/j.enpol.2016.03.013.

Owoade O.K, Fawole O.G, Olise F.S, Ogundele L.T, Olaniyi H.B, Almeida M.S, Ho M-D, Hopke P.K, 2013, 'Characterization and source identification of airborne particulate loadings at receptor site classes of Lagos Mega-City, Nigeria, Journal of the Air and Waste Management Association, 63, 9,1026-1035, doi: 10.1080/10962247.2013.793627.

Ozoh O.B, Okwor T.J, Adetona O, Akinkugbe, A.O, Amadi C.E, Christopher Esezobor C, Adeyeye O.O, Ojo O, Nwude V.N, Mortimer K, 2018, 'Cooking Fuels in Lagos, Nigeria: Factors Associated with Household Choice of Kerosene or Liquefied Petroleum Gas (LPG)', International Journal of Environmental Research and Public Health, 15,4, 1-13, doi: 10.3390/ijerph15040641.

Ren, L, Fu, P, He, Y, Hou, J, Chen, J, Pavuluri, C.M, Sun, Y, Wang, Z, 2016, 'Molecular distributions and compound-specific stable carbon isotopic compositions of lipids in wintertime aerosols from Beijing', Scientific Report, 6, 27481, doi.org/10.1038/srep27481.

Rogge W.F, Hildemann L.M. Mazurek M.A. Cass G.R, 1993, 'Sources of fine organic aerosol, 2, Noncatalyst and catalyst-equipped automobiles and heavy-duty diesel trucks', Environmental Science and Technology, 27, 636-651.

Rushdi A. I, El-Mubarak A. H, Lijotra L, Al-Otaibi M. T, Qurban M.A, Al-Mutlaq K.F, Simoneit B. R. T, 2017, 'Characteristics of organic compounds in aerosol particulate matter from Dhahran city, Saudi Arabia' Arabian Journal of Chemistry, 10, S3532-S3547, doi.org/10.1016/j.arabjc.2014.03.001.

Russell A. G, Brunekreef B, 2009, 'A Focus on Particulate Matter and Health', Environmental Science and Technology, 43, 4620-4625, doi.org/10.1021/es9005459

Samara C, Voutsa D, Kouras A, Eleftheriadis K, Maggos T, Saraga D, Petrakakis M, 2014, 'Organic and elemental carbon associated to PM$_{10}$ and PM$_{2.5}$ at urban sites of northern Greece', Environmental Science and Pollution Research, 21:1769-1785, doi 10.1007/s11356-013-2052-8.

Scalan R.S, Smith J.E, 1970, 'An improved measure of the odd-even predominance in the normal alkanes of sediment extracts and petroleum', Geochimica et Cosmochimica Acta, 34, 611-620, doi.org/10.1016/0016-7037(70)90019-0.

Schauer J.J, Kleeman M.J, Cass G.R, Simoneit B.R.T, 1999, 'Measurement of emissions from air pollution sources, 2, C$_1$ through C$_{30}$ organic compounds from medium duty diesel trucks', Environmental Science and Technology, 33, 1578-1587, doi.org/10.1021/es980081n.

Simoneit B.R.T, Sheng G.Y, Chen X.J, Fu J.M, Zhang J, Xu Y.P, 1991, 'Molecular marker study of extractable organic-matter in aerosols from urban areas of China', Atmospheric Environment, Part A, 25, 2111-2129, doi.org/10.1016/0960-1686(91)90088-0.

Simoneit B.R.T, Kobayashi M, Mochida M, Kawamura K, Lee M, Lim H.J, Turpin B.J, Komazaki Y, 2004, 'Composition and major sources of organic compounds of aerosol particulate matter sampled during the ACE-Asia campaign', Journal Geophysical Research, 109, doi:10.1029/2004JD004598.

Simoneit B.R.T, Elias V.O, 2000, 'Organic tracers from biomass burning in atmospheric particulate matter over the ocean', Marine Chemistry, 69, 301-312, doi.org/10.1016/S0304-4203(00)00008-6.

Simoneit B.R.T, Elias V.O, 2001, 'Detecting organic tracers from biomass burning in the atmosphere', Marine Pollution Bulletin, 42, 805-810, doi.org/10.1016/S0025-326X(01)00094-7.

Simoneit B.R.T, Cardoso J.N, Robinson N, 1991, 'An assessment of terrestrial higher molecular weight lipid compounds in aerosol particulate matter over the South Atlantic from about 30–70° S', Chemosphere, 21, 1285-1301, doi.org/10.1016/0045-6535(91)90196-K.

Sojinu S.O, Sonibare O.O, Ekundayo O, Zeng E. Y, 2012, 'Assessing anthropogenic contamination in surface sediments of Niger Delta, Nigeria with fecal sterols and n-alkanes as indicators', Science of the Total Environment 441,89-96, doi.org/10.1016/j.scitotenv.2012.09.015.

Stein A.F, Draxler R.R, Rolph G. D, B. Stunder J. B, Cohen M. D, Ngan F, 2015, 'NOAA's HYSPLIT Atmospheric Transport and Dispersion Modeling System', Bulletin of the American Meteorological Society, 96, 2059-2077, doi.org/10.1175/BAMS-D-14-00110.1.

Sun N, Li X, Ji Y, Huang H, Ye Z, Zhao Z. 2021, 'Sources of PM$_{2.5}$-Associated PAHs and n-alkanes in Changzhou China', Atmosphere, 12, 9,1127, doi.org/10.3390/atmos12091127.

Tang X.L, Bi X.H, Sheng G.Y, Tan J.H, FU J.M, 2006, 'Seasonal variation of the particle size distribution of n-alkanes and polycyclic aromatic hydrocarbons (PAHs) in urban aerosol of Guangzhou, China', Environmental Monitoring Assessment, 117, 193-213, doi.org/10.1007/s10661-006-0440-y.

Tian S, Liu Y, Wang J, Wang J, Hou L, Lv B, Wang X, Zhao X, Yang W, Geng C, Han B, Bai Z, 2020, 'Chemical compositions and source analysis of PM$_{2.5}$ during autumn and winter in a heavily polluted city in China', Atmosphere, 11, 336, doi.org/10.3390/atmos11040336.

Turpin B.J, Lim H.J, 2001, 'Species Contributions to PM$_{2.5}$ Mass Concentrations: Revisiting Common Assumptions for Estimating Organic Mass', Aerosol Science and Technology, 35, 602-610, doi.org/10.1080/02786820119445, 2001.

Van Pinxteren M, Fiedler B, Van Pinxteren D, Iinuma Y, Körtzinger A, Herrmann H, 2015, 'Chemical characterization of sub-micrometer aerosol particles in the tropical Atlantic Ocean: marine and biomass burning influences', Journal of Atmospheric Chemistry, 72, 105–125, https://doi.org/10.1007/s10874-015-9307-3.

Wang G, Huang L, Zhao X, Niu H, Dai Z, 2006, 'Aliphatic and polycyclic aromatic hydrocarbons of atmospheric aerosols in five locations of Nanjing urban area, China', Atmospheric Research, 81, 54-66. doi.org/10.1016/j.atmosres.2015.09.007.

WHO (World Health Organization) 2021, 'WHO global air quality guidelines, Particulate matter (PM$_{2.5}$ and PM$_{10}$), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide', Geneva.

Yang J, Lei G, Liu C, Wu Y, Hu K, Zhu J, Bao J, Lin W, Jin J, 2023, 'Characteristics of particulate-bound n-alkanes indicating sources of PM$_{2.5}$ in Beijing, China', Atmospheric Chemistry and Physics, 23, 3015-3029, 2023, doi.org/10.5194/acp-23-3015-2023.

Yttri K.E, Simpson D, Bergström R, Kiss G, Szidat S, Ceburnis D, Eckhardt S, Hueglin C, Nøjgaard J.K, Perrino C, Pisso I, Prevot A.S.H, Putaud J.-P, Spindler G, Vana M, Zhang Y.-L, Aas W, 2019,

'The EMEP Intensive Measurement Period campaign, 2008–2009: characterizing carbonaceous aerosol at nine rural sites in Europe', Atmospheric Chemistry and Physics, 19, 4211-4233, https://doi.org/10.5194/acp-19-4211-2019.

Yu J.Z, Huang X. H. H, Ho S. S. H, Bian Q, 2011, 'Nonpolar organic compounds in fine particles: quantification by thermal desorption–GC/MS and evidence for their significant oxidation in ambient aerosols in Hong Kong', Analytical and Bioanalytical Chemistry, 401, 3125-3139, doi 10.1007/s00216-011-5458-5.

Zeng L, Offor F, Zhan L, Lyu X, Liang Z, Zhang L, Wang J, Cheng H, Guo H, 2019, 'Comparison of PM₂.₅ pollution between an African city and an Asian metropolis', Science of the Total Environment , 696, 134069, doi.org/10.1016/j.scitotenv.2019.134069.

Zhang N, Cao J, Li L, Ho S.S.H, Wang Q, Zhu C, Wang L, 2018, 'Characteristics and Source Identification of Polycyclic Aromatic Hydrocarbons and n-Alkanes in PM₂.₅ in Xiamen', Aerosol and Air Quality Research, 18,1673-1683, doi.10.4209/aaqr.2017.11.0493.