Describing Aerosol and Assessing Health Effects in Lima, Peru

Odón R. Sánchez-Ccoyllo, Carol Geimy Ordoñez-Aquino, Jessica Arratea-Morán, Nélida S. Marín-Huachaca, and Warren Reátegui-Romero

Abstract—**The current study aims to discover the chemical-morphological characteristics of PM_{10} through the analysis of Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) and Scanning Electron Microscopy (SEM), respectively, in the Metropolitan Area of Lima (MEAL) in the period from January 04 to 18, 2019. The study also aims to analyze the aerosol optical depth (AOD) in the period from January 1, 2014 to October 15, 2020. The effect of the $PM_{2.5}$ concentrations on health in 2016 has also been quantified. The results indicate that the daily PM_{10} value of 50 $\mu g/m^3$ recommended by the World Health Organization was exceeded on 75% of the monitored days. The morphological analysis of PM_{10} demonstrated the presence of particles of anthropogenic and geogenic origin. Particles from building activities and secondary aerosol formation were found, as well as particles associated with the resuspension of soil and marine aerosols. In 2016, 718, 1426, and 4295 cases of all-cause mortality, on average, could have been avoided in the MEAL if the annual average of $PM_{2.5}$ would have decreased from 26.53 $\mu g/m^3$ to 23.88 $\mu g/m^3$, 21.22 $\mu g/m^3$, or 10 $\mu g/m^3$, respectively. In 2016, 1.58%, 3.14% and 9.47% of all causes are respectively attributed to fine aerosol ($PM_{2.5}$) over 23.88 $\mu g/m^3$, 21.22 $\mu g/m^3$, and 10 $\mu g/m^3$. Policy makers to legally reduce the $PM_{2.5}$ concentrations in the MEAL could use this result.**

Index Terms—**ICP-AES, Lima, PM_{10}, SEM, trace metals.**

I. INTRODUCTION

Atmospheric pollutants kill seven million people every year on the planet, and 9 out of 10 people breathe air that exceeds the limits for pollutant concentrations according to the World Health Organization (WHO) [1]. The combined effects of outdoor and household air pollution lead to mortality from stroke [2]; heart diseases [3], [4]; lung cancer [4]; breathing infections [5]; asthma [6]; negatively affected pregnancies, and poor birth outcomes [4], [7]. A mixture of organic and inorganic materials of solid particles and liquid droplets is named particulate matter (PM), [8]-[13]. PM in the receptor is called an aerosol [14]. Some particles are microscopic; therefore, they become visible through an electron microscope. PM is composed of chemicals such as sulfates, nitrates, carbon, or mineral powders [5], [15]-[18].

Natural processes affect air quality and anthropic activities; industrial and vehicle emissions [19]; cigarette smoke; and burning of organic matter can compose PM [5]. A "mega city is defined as a city with more than ten million people" [20], [21], where atmospheric pollutants are a significant public health problem [22]. PM with aerodynamic diameter smaller than 10 μm or 2.5 μm (PM_{10} and $PM_{2.5}$) is harmful for people's health [16], [23], [24] because of its capacity to move into the lungs and even the bloodstream [15], [16], [21]. The Metropolitan Area of Lima and Callao (MEAL) with a population of more than 10.6 million people [25] is one of the most polluted cities in South America [26]. MEAL has a network air quality of 17 stations in total that are operated by the Peruvian Government and which are distributed in North Lima, East Lima, Center Lima, and South Lima. The daily concentrations of particles in the MEAL often exceed the Peruvian National Ambient Air Quality Standards as well as the WHO air quality guideline [27]. The most polluted areas in the MEAL are found in North and East Lima [28]. These areas are influenced by the "thermal inversion layer further increasing exposure level, which drops during the summer rather than during the winter to a base height of approximately 500 meters" [29]. Thus, for us, it is more important to research PM in the summer. The concentration of PM_{10} in South Lima is worrisome because South Lima has industry and poor greens areas. The MEAL's population is breathing high concentrations of $PM_{2.5}$ [30]. High PM concentrations compromise the health at risk of people in Lima [31]. WHO's European Centre for Environmental Health developed the AirQ+ software that allows researchers to assess the effect on human health [32]-[34]. This model has been used to estimate the effect of $PM_{2.5}$ on mortality [35]-[37] and the results can be used to help decision and policy-makers understand health benefits associated with decreased $PM_{2.5}$ concentrations [32], [36]. On other hand, satellite data of Aerosol Optical Depth (AOD) are elemental for air quality monitoring [38], [39]. The "Moderate Resolution Imaging Spectroradiometer" (MODIS) sensor allows for a special opportunity for obtaining AOD information [40]. The main objectives of this research were: 1) To determine the chemical-morphological characteristics of PM_{10} using Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES), and the Scanning Electron Microscope coupled with Energy Dispersive X-ray Spectrometry (SEM- EDS) in the Villa El Salvador district, Lima, Peru, from January 04 to 18, 2019. 2) To analyze the

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daily AOD from January 01, 2014 to October 15, 2020 in the MEAL. Moreover, 3) To estimate health effects of long-term exposure to $PM_{2.5}$ concentrations on residents in the MEAL megacity by applying the AirQ+ model to study all cause-mortality rates in 2016. For the first time, the PM_{10} concentration measurements, PM_{10} metal analysis with ICP-AES, and PM_{10} aerosol morphology analysis with SEM-EDS were performed at the National Technological University of South Lima (UNTELS) located in the Villa El Salvador district at Southern MEAL. Furthermore, the study consists of a different analysis where three types of scenarios of decreasing $PM_{2.5}$ concentrations have been considered to quantify the health impact of long-term exposure to $PM_{2.5}$ concentration using WHO´s AirQ+ model, which is not available in other research in the MEAL. Finally, to the authors' knowledge, this is probably the first study to analyze the daily AOD, the AOD annual cycle, and the AOD annual variation. AOD values are spatial resolution of 1 °* 1 °level three from 2014 to 2020 in the MEAL.

II. METHODOLOGY

A. PM_{10} Sampling Site and Chemical-Morphological Analysis

The sampling was performed on the UNTELS campus (12°12'51.03″ South, 76°55'58.31″ West) located at the intersection of the Central and Bolívar Avenues, main routes for public transportation displacement (see Fig. 1). UNTELS is 3.7 km from the sea, and located in the Villa El Salvador district (Lima 42), in the southern part of the MEAL. This district has a population of 423,887 inhabitants [25]. The land use is predominantly residential, followed by industrial use. The PM_{10} samples were collected with a High Volume Air Sampler (Hi-Vol, TISCH brand, USA) from January 04 to 18, 2019, in sample periods of 24 hours and 12 hours according to the IO-3.4 US EPA Norm [41]. The Hi-Vol equipment was calibrated beforehand according to the IO-2.1 US EPA Norm [42]. The Hi-Vol instrument was operated on the terrace of Building E at UNTELS at a height of approximately 15-20 meters above ground in a location with no obstructions. All daily sample flow rates were identified at 1.13 m^3/min during the sampling period from January 04 to January 18, 2019. Samples were collected on pre-weighed 8" x 10" Whatman quartz microfiber filters (GE Healthcare Life Sciences Whatman^{TM}, China) filters.

The analysis with ICP-AES provided us with quantitative information on the trace elements concentration of the daily samples (24 hours) from January 08 to 11, 2019. The concentrations of PM_{10} were calculated by dividing the mass of the collected PM_{10} by the total volume [43]. Using the SEM-EDS, the chemical-morphological analysis was performed on the PM_{10} samples from January 15 to 18, 2019 in 12-hour sample periods. For scanning electron microscopy (SEM) analyses, the PM_{10} filters were coated with carbon. Backscattered electron figures were taken to visualize areas of dissimilar chemical compositions. The PM_{10} photomicrographs (SEM) provided valuable information regarding characteristics of the particulate material, such as shape (irregular, smooth, angular, etc.), size – characterized by its aerodynamic diameter – and, the porosity of the particle. These analyses provided an elemental chemical analysis, and could reveal characteristics about the type of PM_{10} source or origin.

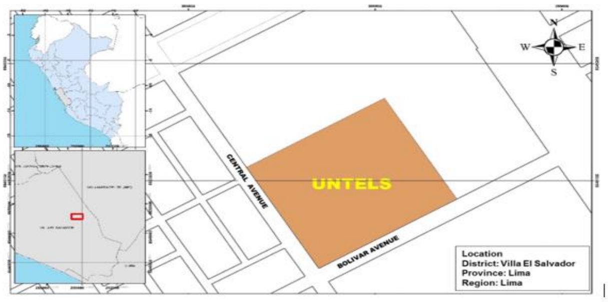

Fig. 1. Location of the sampling point.

B. Daily Aerosol Optical Depth (AOD)

The daily AOD data was measured with the MODIS sensor, which is on-board of the Aqua MODIS at 550 nm (AOD550). The AOD values were obtained from the Giovanni website (https://giovanni.sci.gsfc.nasa.gov/giovanni/) in the period from January 01, 2014 to October 15, 2020 with spatial resolution of 1 °* 1 °level 3 (grid points). The daily average value of AOD550 for the MEAL was obtained from the following coordinate: latitude between 11.3 South and 12.7 South, longitude between 77.7 West and 76.1 West. The (MOD08_M3_v6.1) MODIS sensor is on-board the NASA's "Earth Observing System Aqua and Terra space crafts" polar orbit. The Terra satellite passes by around 10:30 LST, while the Aqua satellite crosses the equator northward around 13:30 LST [40], [44], [45].

The annual cycle of AOD values was developed from the daily AOD550 values. For the average AOD for January from 2014 to January 2020, all the daily values of AOD550 for the months of January's 2014, 2015, 2016, 2017, 2018, 2019 and 2020 have respectively been used. To calculate the average AOD for February, March, April up to December from 2014 to 2020 the same methodology developed for the average AOD for January from 2014 to 2020 as described above was used. In addition, to calculate annual AOD averages from 2014 to 2020, the following methodology described as follows was used. To calculate the average of AOD for 2014, the daily AOD550 data for 2014 was used. To calculate the average AOD for 2015, the daily AOD550 data for 2015 was used, and so forth, until calculating the average AOD for the year 2020.

C. The $PM_{2.5}$ Effect on Human Health

In this study, WHO's AirQ+ model [46] was used to quantify the health impact from long-term exposure to $PM_{2.5}$ concentrations. Three types of data were used for this air quality model: i) Choosing the research place (in this study it ended up being the MEAL); ii) Population and mortality data in 2016 (total population was 10,030,510 residents; population over 30 years-old was 5,179,557; total mortality regarding people over 30 years old was 45,373); and, iii) The annual average $PM_{2.5}$ concentrations in 2016 was 26.53 μg/m^3. These data were provided by the Peruvian Ministry of the Environment and processed into the AirQ+ version V2.0 model. In this study, premature deaths due to long-term $PM_{2.5}$ exposures was estimated considering three scenarios: i) Reducing the annual average $PM_{2.5}$ concentrations by 10%, from 26.53 µg/m^3 to 23.88 µg/m^3; ii) Reducing the annual average $PM_{2.5}$ concentrations by 20%, from 26.53 µg/m^3 to 21.22 µg/m^3; and, iii) Reducing the annual average $PM_{2.5}$ concentrations to the WHO's recommended value, 10 µg/m^3. The variables required for applying the AirQ+ (version V2.0) model are shown in Table I. The AirQ+ model is established in the attributable ratio, which is the health effect fraction attributed to exposure to air pollution such as annual $PM_{2.5}$ concentrations by residents in the MEAL [37], [47] (Equation 1):

$$APRO = \sum((RR-1).RI)/\sum(RR.RI) \qquad (1)$$

where *RR* is the relative risk for a specific health endpoint when exposed to $PM_{2.5}$ concentrations and *RI* is the population selected (in the MEAL) that was exposed to $PM_{2.5}$ concentrations. The number of health effect inferable to the exposure (HEE) and the amount of cases attributable to the exposure (AE) could be calculated by respectively 2 and 3 equations techniques [36], [47]:

$$HEE = BI.APRO \qquad (2)$$

$$AE = HEE.SP \qquad (3)$$

where *BI* is the baseline incidence of health effect on the inhabitants (see Table I) and *SP* is the magnitude of population under study.

TABLE I: LONG-TERM HEALTH ENDPOINT AND BASELINE INCIDENCE (BI) RATE OF DISEASE

Health Endpoint	Baseline Incidence[1]	Age	Pollutant	RR2 (95% CI) per 10 µg/m^3
Mortality – all (natural causes)	876	Adults ≥ 30	$PM_{2.5}$	1.062 (1.04-1.083)

[1] Crude rate per 100, 1000 inhabitants.

[2] RR reference is [48].

III. RESULTS AND DISCUSSION

A. Daily PM_{10} Concentrations

Fig. 2 shows the daily variation of the PM_{10} concentrations from January 04 to 18, 2019. The minimum and maximum concentrations were 40.5 µg/m^3 and 76 µg/m^3, recorded on January 07 and 18, respectively. Furthermore, on 75% of the days the value recommended by the WHO (50 µg/m^3) was exceeded; but none exceeded the established Peruvian National Ambient Air Quality Standard (PNAAQS) concentration of 100 µg/m^3 for PM_{10}. In the period from January 04 to 07, 2019, there was a strong synoptic condition (the South Pacific Subtropical High (SPSH)) with a high atmospheric pressure center of 1030 hPa located at 36°S, 100°W latitude and longitude, respectively. The SPSH condition generated a SE wind direction. This SE wind direction brings moisture to UNTELS, which contributes to lower PM_{10} concentrations at UNTELS. By contrast, for the period from January 08 to 18, 2019, there was a weak SPSH with a high pressure of 1023 hPa causing a warm period, without drizzle, and weak wind velocity. This NW wind may be associated with high PM_{10} values at UNTELS (Fig. 2). Thus, for these meteorological conditions the PM_{10} concentrations were increasing from the very start of the sampling on January 04, 2019 until the research was finished on January 18, 2019 (Fig. 2).

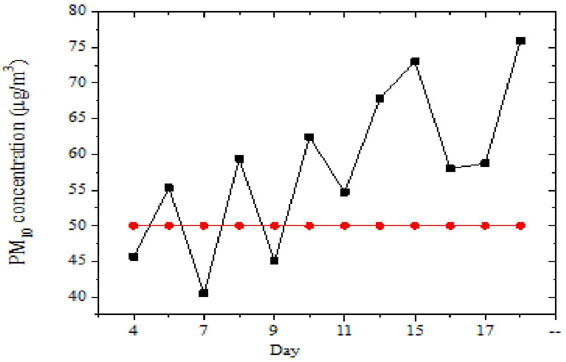

Fig. 2. Daily average of the PM_{10} concentrations from 04 to 18 January 2019. The red line indicates the corresponding PM_{10} limit values recognized by WHO.

B. PM_{10} Chemical Analysis with ICP-AES

The average concentration and standard deviation of trace elements Al (403.3 ng/m^3 ± 80.8 ng/m^3), Cu (24.6 ng/m^3 ± 3.3 ng/m^3), Fe (705.9 ng/m^3 ± 151.7 ng/m^3), Mg (499.2 ng/m^3 ± 51.2 ng/m^3), Na (1919.6 ng/m^3 ± 253.6 ng/m^3), P (87.2 ng/m^3 ± 12.6 ng/m^3), Si (615.6 ng/m^3 ± 92.8 ng/m^3), and Sr (7.8 ng/m^3 ± 1.0 ng/m^3), in the period from January 08 to 11, 2019 are shown in Fig. 3. According to these results, the ratio between the concentration of Fe and Cu was 28.7. This can be explained by remains of building constructions of approximately 12 years ago near the chosen sampling site due to a High Volume Air Sampler (Hi-Vol) safety at UNTELS. Moreover, the Hi-Vol instrument was operated on a terrace building at UNTELS approximately 15-20 meters above the surface. At this altitude, the wind velocity was higher than the wind velocity at the surface in the sampling period when the high wind velocity at 15-20 m altitude could generate soil resuspension. Therefore, for these reasons the Fe-concentrations contained a higher Fe-value (Fig. 3). In a study conducted by [49], this ratio was 171.42 in Dhaka, Bangladesh, indicating a high concentration of iron. High Fe-concentrations come from soil dust, building construction, etc., so it is natural and anthropogenic. High values of Na-concentrations were noted. Most likely due to the sampling place as it is located close to sea and there are construction activities near the sampling site (see Fig. 3). In urban areas, construction activities contribute to high Na-concentrations in the atmosphere [50], [51]. The combustion of coal, tires rubber abrasion, and brakes are the main contributors of Cu and other elements such as Pb [49], [52]. Assuming the presence of Si as silica (SiO_2), it is known that silica is toxic because of prolonged exposure to fine particles causing a disease called silicosis that affects the respiratory tract and generates lung cancer [53]-[55]. In a study in India, the Si-concentration in PM_{10} was 15900 ng/m^3 [52]. Sea salt particles contribute significantly to PM_{10} observed in coastal areas [56]. In this study, the average concentrations of trace elements are demonstrative due to the very limited number of samples that was used. Therefore, it is worth mentioning that this study has had limited day samples of the PM_{10} concentrations as there was not enough money to perform samples for a longer period of time, for example, for two months at UNTELS. In spite of having trace elements information for only four days, the results give us a glimpse of the situation in South Lima.

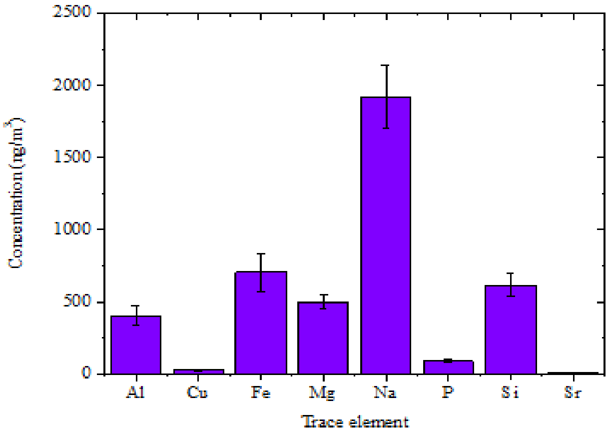

Fig. 3. Metal concentrations in PM_{10} in Lima (January 8-11, 2019).

The correlations between the trace elements were evaluated using the Pearson coefficient as shown in Table II. The soil source elements (for instance Al, Fe, Mg, and Si) have a high positive Pearson ́s correlation. High correlations were found between Al and Fe (0.998; $p < 0.01$); between Al and Sr (0.977; $p < 0.05$); and between Fe and Sr (0.962 $p < 0.05$).

TABLE II: PEARSON CORRELATION OF THE TRACE ELEMENTS IDENTIFIED IN PM_{10}

	Al	Cu	Fe	Mg	Na	P	Si	Sr
Al	1	0.944	0.998**	0.928	-0.066	0.822	0.940	0.977*
Cu		1	0.947	0.997	-0.014	0.967	0.775	0.971
Fe			1	0.931	-0.021	0.851	0.936	0.962*
Mg				1	0.260	0.922	0.746	0.934
Na					1	0.503	-0.338	-0.101
P						1	0.640	0.759
Si							1	0.886
Sr								1

** At $p < 0.01$ The correlation is significant.

* At $p < 0.05$ The correlation is significant.

C. PM_{10} Chemical — Morphological Analysis with SEM-EDS

Eleven trace elements as well as oxygen were identified. All together, they added up to 100%. These trace elements are Na (0.82%), Al (0.66%), Ca (0.53%), S (0.31%), Mg (0.26%), Cl (0.25%), Fe (0.12%), K (0.10%), Cu (0.05%), Ti (0.05%), and Cu (0.04%). Oxygen is mainly present in oxide and white filter silicon. The predominant trace elements were classified in six categories: 1) Chlorine particles, presence of sodium chlorides. This is due to the fact that the MEAL megacity is close to sea, in addition to calcium chlorides (see Fig. 4). The chemical analysis of water soluble ions carried out in cities near the sea reveal the presence of sodium chloride, and the ratio of its ions is mainly equimolecular [57]; 2) Silica particles, due to the presence of conglomerates of iron, calcium, aluminum, sodium, titanium, calcium, and magnesium particles, in the form of goethite and pyrite, which is associated with soil resuspension (see Fig. 5). Goethite is the most common of the iron oxyhydroxides [58]. Goethite is present in Fe-oxide mineral in soils [59]; 3) Sulfur particles, presence of calcium sulfates (gypsum), barium sulfate (barite), calcium sulfate, copper sulfide, associated with secondary aerosol formation (see Fig. 6). The ratio of the sulfate concentration in aerosol during daytime and during nighttime is greater than one. Due to the photochemical effect [57]. Gypsum ($CaSO_4$ $2H_2O$), it is the most common of the sulphate minerals [60], 4) Oxides, presence of iron oxide, typical of soil resuspension, but also the presence of tin oxide and copper oxide due to fossil fuel combustion (see Fig. 7). About 50 elements are present in coal [61], [62]; 35 in crude oil [63]; 5) Calcium particles, presence of calcium carbonate usually used by cement companies (see Fig. 8a); and, 6) Metals, due to the presence of lead, molybdenum and zircon (see Fig. 8b). The results indicate that the identified particles mostly belong to geogenic and anthropogenic sources. The presence of marine aerosol has also been found in other coastal cities such as Peshawar, Pakistan [64]. In addition, calcite (NaCl) particles were found in Sao Paulo, Brazil, which is 60 km away from the Atlantic Ocean [65]. The presence of silicates in general is associated with the resuspension of soil by wind or by the passing of vehicles [66]. Silicon concentrations are predominant in PM_{10} particles [67].

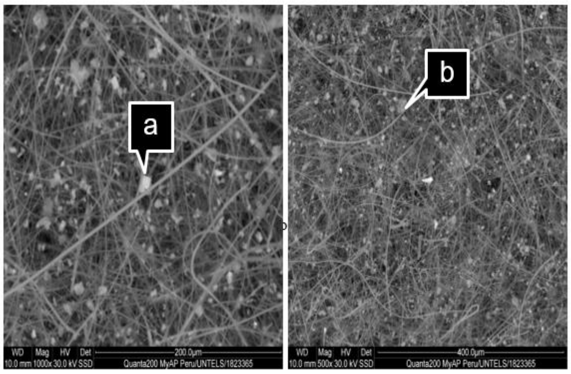

Fig. 4. PM_{10} Photomicrographs, a) Sodium chloride; and b) Calcium chloride.

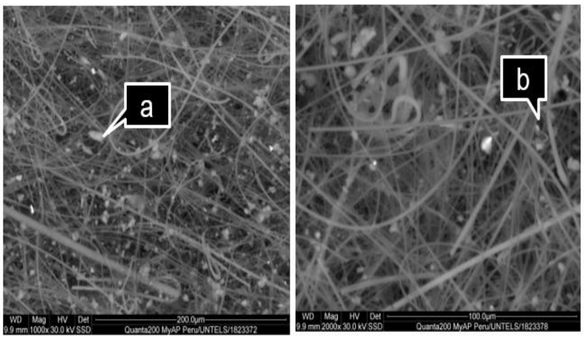

Fig. 5. PM_{10} Photomicrographs, a) Silicates; and, b) Si, Fe, Cl, Na, Ca agglomerate.

D. Daily OAD

In the MEAL, the daily AOD often ranges from 0.02 to 0.45 (see Fig. 9), but sometimes the AOD value reaches 0.6.

While on some days, they reached the peak values of 0.9 (June 4, 2018); 0.76 (April 28, 2015); and, 0.73 (August 7, 2020). The plot represents the AOD mean (black square) and the median (red horizontal line). The plot also shows the extreme observations as diamonds. These values correspond with the meteorology conditions in the MEAL because Lima is under the influence of persistent atmospheric stability whereby its sky is always covered by clouds [29].

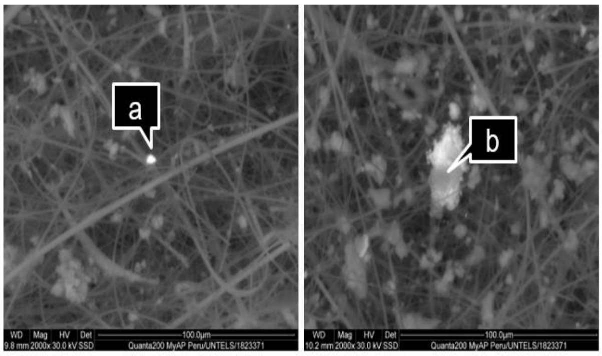

Fig. 6. PM_{10} Photomicrographs. a) Barite; and, b) Copper sulfide.

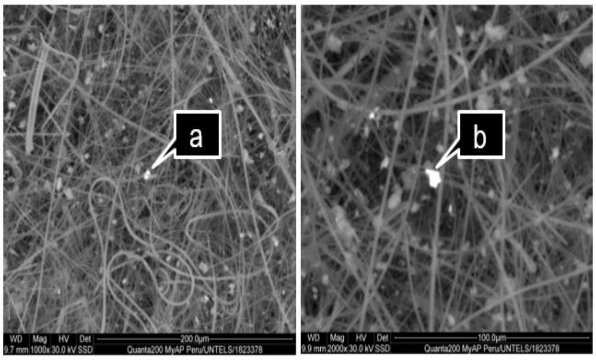

Fig. 7. PM_{10} Photomicrographs. a) Iron oxide; and, b) Tin oxide.

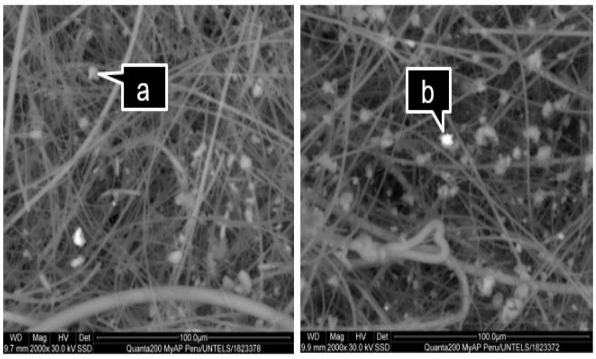

Fig. 8. PM_{10} Photomicrographs. a) Calcium carbonate; and b) Lead.

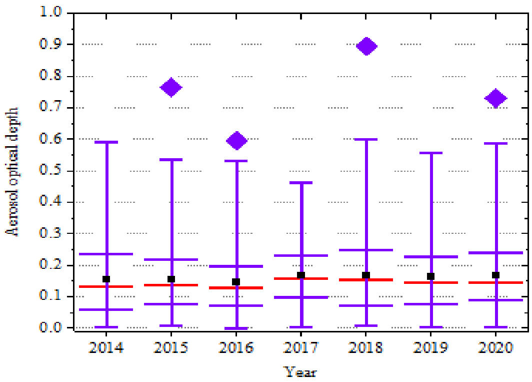

Fig. 9. AOD variability measured with the MODIS sensor on-board the Aqua satellite from January 01, 2014 to October 15, 2020.

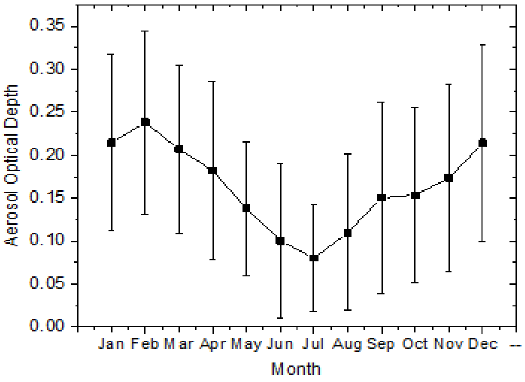

Fig. 10. Annual MODIS-AOD cycle over Lima from 2014 to 2020. The vertical bars indicate standard deviations.

Fig. 10 shows the annual AOD cycle obtained from MODIS-Aqua over the MEAL from 2014 to 2020. The lowest monthly AOD values in the period from 2014 to 2020 take place in June, July, and August (Fig. 10). In June, the average AOD is 0.10, and the AOD value varies from 0.001 to 0.20. In July, the AOD value varies from 0.019 to 0.14 with an average AOD of 0.1. The AOD value in the month of August varies from 0.019 to 0.2, with an average AOD value of 0.11. The lowest AOD values are observed in the months of June to August (the winter season in Lima). This may be due to the drizzle in Lima, which in the winter season is 1 mm/year.

While, high monthly-AOD values in the period from 2014 to 2020 are observed in the months of January, February, March, April, November, and December (Fig. 10). In January, the AOD values vary from 0.11 to 0.32 with an average AOD of 0.21 in January. In February, the AOD values vary from 0.14 to 0.35 with an average AOD value of 0.24 in February. In the month of March, the AOD values vary from 0.11 to 0.31 with a mean value of 0.21. In April, the AOD values vary from 0.08 to 0.29 with a mean value of 0.18 (Fig. 10). In November, the AOD values vary from 0.07 to 0.28 with a mean value of 0.17. In December, the AOD values vary from 0.1 to 0.33 with a mean of 0.21 (Fig. 10). High AOD values are observed in the months of January to April and the months of November and December, which may be due to the absence of drizzle and higher temperatures with an average temperature in summer season of 22.5 ℃ in the MEAL. The summer months (January, February and March) have elevated AOD values. That is similar to what has been found in Pakistan where in the summer season there are higher AOD values due to higher temperatures during the summer season in Pakistan [68]. The temporal annual average of AOD values have been very similar each year from 2014 to 2020 (0.15 ±0.12), (0.15 ±0.11), (0.14 ±0.1), (0.17 ±0.09), (0.17 ±0.12), (0.16 ±0.11), (0.17 ±0.11), respectively.

E. AirQ+ Model Analysis

The number of premature deaths related to long-term exposure to annual $PM_{2.5}$ concentrations and the uncertainty for three scenarios of $PM_{2.5}$ concentrations in the MEAL in 2016 were evaluated (Table III). The following hypothetical scenarios were considered: i) Reducing the annual concentration of $PM_{2.5}$ in the MEAL by 10%. The same said in other words, if the annual $PM_{2.5}$ concentrations do not exceed 23.88 $\mu g/m^3$; ii) Reducing the annual $PM_{2.5}$ concentrations in the MEAL by 20%, or if the annual $PM_{2.5}$

concentrations do not exceed 21.22 μg/m^3; and, iii) Reducing the PM$_{2.5}$ annual concentrations to 10 μg/m^3 recommended by WHO.

Approximately 718 [95% confidence interval (95% CI): 469, 949] non-accidental deaths could have been avoided by decreasing PM$_{2.5}$ exposures by 10% in 2016, resulting in a 1.58% decrease in total mortality in the MEAL. In the second scenario, we estimated that 1426 [(95% CI): 935, 1881] non-accidental deaths due to PM$_{2.5}$ exposures could have been avoided. In the third scenario, if the annual PM$_{2.5}$ concentrations would not have exceeded 10 μg/m^3, 4,295 (95% CI: 2848, 5603) non-accidental deaths could have been avoided (Table III). Reference [32] showed that the number of all-cause deaths in adults (older than 30 years) were approximately 600 (95 %CI: 400-800) due to long-term exposure to PM$_{2.5}$ in the city of Tabriz, Iran in 2016. This represented a 7.3% mortality rate.

TABLE III: ASSESSMENT OF THE NUMBER OF EXCESS CASES FROM 3 PM$_{2.5}$ CONCENTRATIONS SCENARIOS AND 95% CI IN THE MEAL IN 2016

Health Endpoint	Three PM$_{2.5}$ Scenarios	Relative Risk	Evaluate APRO (%)	Calculated number of excess deaths
All-cause Mortality	Reduce PM$_{2.5}$ by 10% (23.88 μg/m^3)	Lower	1.03	469
		Central	1.58	718
		Upper	2.09	949
	Reduce PM$_{2.5}$ by 20% (21.22 μg/m^3)	Lower	2.06	935
		Central	3.14	1426
		Upper	4.15	1881
	Reduce to what is recommended by WHO (10 μg/m^3) annually	Lower	6.28	2848
		Central	9.47	4295
		Upper	12.35	5603

IV. CONCLUSION

In summary, in seventy-five percent of the monitored days in the MEAL daily values of PM$_{10}$ concentrations exceeded the threshold of 50 μg/m^3 suggested by the WHO guidelines. The PM$_{10}$ chemical analysis with the ICP-AES technique determined that the main sources of contamination originated from the soil (Al, Fe, Mg, Si), vehicles (Cu), and the marine environment (Na). The PM$_{10}$ morphological analysis demonstrated the presence of particles of anthropogenic origin due to the presence of particles associated with the combustion of fossil fuel as well as construction activities and secondary aerosol formation and of geogenic origin due to the presence of particles associated with the resuspension of soil and marine aerosols.

Moreover, long-term health effects were estimated using WHO's AirQ+ model in the MEAL megacity in 2016 for all-cause mortality. The result indicated that reducing long-term exposure to ambient air pollution can decrease mortality by 1.58% (1.03 to 2.09) when PM$_{2.5}$ is reduced by 10%; 3.14% (2.06 to 4.15) if PM$_{2.5}$ is reduced by 20%; and 9.47% (6.28 to 12.35) if PM$_{2.5}$ is reduced to the annual WHO guideline of PM$_{2.5}$. These results can provide evidence for recommendations for policy-makers to reduce fine particulate matter in the MEAL megacity [69]. The present-day PM$_{2.5}$ concentrations in the MEAL are an important human health threat that, if reduced, could prevent hundreds to thousands of deaths [69]. A deeper insight in order to identify the main sources of atmospheric aerosol using the receptor model is needed in the MEAL in the future.

CONFLICT OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.

AUTHOR CONTRIBUTIONS

O.R. Sánchez performed the PM$_{10}$ sampling, designed the methodology, worked on the figures, the writing –of the original draft. Carol Ordoñez interpreted the SEM results. Jessica Arratea performed the conceptualizations. W. Reátegui: Worked on the writing – review and editing. N. Marín-Huachaca analyzed the particulate matter concentration data. All authors provided bibliographic references, final comments, and approved the final version of the article.

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REFERENCES

[1] WHO, "Air pollution," World Health Organization (WHO), Geneva, 2020.

[2] M. Leiva, D. Santibañez, S. Ibarra, P. Matus, and R. Seguel, "A five-year study of particulate matter (PM2.5) and cerebrovascular diseases," *Environmental Pollution*, vol. 181, pp. 1-6, 2013.

[3] R. Williams, R. Brook, R. Bard, T. Conner, H. Shin, and R. Burnett, "Impact of personal and ambient-level exposures to nitrogen dioxide and particulate matter on cardiovascular function," vol. 22, pp. 71-91, 2012.

[4] Z. Sun and D. Zhu, "Exposure to outdoor air pollution and its human health outcomes: A scoping review," *PLOS ONE*, vol. 14, pp. 1-18, 2019.

[5] NIH, "Air pollution and your health", National Institute of Environmental Health Sciences, 2020.

[6] J. Goodman, K. Zu, C. Loftus, G. Tao, X. Liu, and X. Lange, "Ambient ozone and asthma hospital admissions in Texas: A time-series analysis," *Asthma Research Practice*, vol. 3, pp. 1-10, 2017.

[7] S. Ha, R. Sundaram, G. Buck, G. Nobles, I. Seeni, S. Sherman, and P. Mendola, "Ambient air pollution and the risk of pregnancy loss: A prospective cohort study," *Environment*, vol. 109, pp. 148-153, 2018.

[8] Y. Tsai and M. Cheng, "Characterization of chemical species in atmospheric aerosols in a metropolitan basin," *Chemosphere*, vol. 54, pp. 1171-1181, 2004.

[9] A. Huamán, Y. Bendezu, L. Suarez, J. Pomalaya, D. Alvarez, and A. Gioda, "Chemical characterization of PM2.5 at rural and urban sites around the metropolitan area of Huancayo (Central Andes of Peru)," *Atmosphere*, vol. 10, pp. 1-17, 2019.

[10] S. Ciuta, D. Tsiamis, and M. Castaldi, "Chapter five — Emissions," *Gasification of Waste Materials*, San Diego, United States., Elsevier, 2018, pp. 93-119.

[11] Y. Chirino, Y. Sánchez, A. Osornio, I. Rosas, and C. García, "Sampling and composition of airborne particulate matter (PM10) from two locations of Mexico City," *Data in Brief*, vol. 4, pp. 353-356, 2015.

[12] A. Salam, M. Assaduzzaman, M. Nobi, and A. Alam, "Water soluble ionic species in the atmospheric fine particulate matters (PM2.5) in a Southeast Asian Mega City (Dhaka, Bangladesh)," *Open Journal of Air Pollution*, vol. 4, pp. 99-108, 2015.

[13] Y. Zhu and H. Frey, "Integrated gasification combined cycle (IGCC) systems," *Combined Cycle Systems for Near-Zero Emission Power Generation*, Cambridge,UK., Woodhead Publishing Limited, 2012, pp. 129-161.

[14] M. Okubo and T. Kuwahara, "Chapter 2 — Emission regulations," *New Technologies for Emission Control in Marine Diesel Engines*, Cambridge, MA., Butterworth-Heinemann, 2020, pp. 25-51.

[15] USEPA, "Particulate matter (PM) basics," United States of Environmental Protection Agency, 2020a.

[16] M. Okubo and T. Kuwahara, "Emission regulations," *New Technologies for Emission Control in Marine Diesel Engines*, MA, US., Elsevier, 2020, pp. 25-51.

[17] T. Gordon, L. Stanek, and J. Brown, "Pollution air," *Encyclopedia of Toxicology* (Third Edition), MD, USA, Academic Press, 2014, pp. 995-1002.

[18] J. Geddes and J. Murphy, "The science of smog: A chemical understanding of ground level ozone and fine particulate matter," *Metropolitan Sustainability Understanding and Improving the Urban Environment*, 2012, pp. 205-230.

[19] M. Galletti, S. Castellini, A. Pileri, C. Austeri, M. Pompei, and M. Angelucci, "Chemical characterization of PM10 particulate matter in the ambient air of a region of Central Italy (Umbria)," *International Journal of Analytical Mass Spectrometry and Chromatography*, vol. 3, pp. 47-53, 2015.

[20] Y. Miao, J. Li, S. Miao, H. Che, Y. Wang, X. Zhang, R. Zhu, and S. Liu, "Interaction between planetary boundary layer and PM2.5 pollution in megacities in China: A review," *Air Pollution*, vol. 5, pp. 261–271, 2019.

[21] M. Krzyzanowski, J. Apte, S. Bonjour, M. Brauer, A. Cohen, and A. Prüss, "Air pollution in the mega-cities," *Global Environmental Health and Sustainability*, vol. 1, pp. 185-191, 2014.

[22] J. Molina and L. Molina, "Megacities and atmospheric pollution," *Journal of the Air & Waste Management Association*, vol. 54, pp. 644-680, 2012.

[23] D. Sarkar, "Chapter 14 — Air pollution control," *Thermal Power Plant*, Amsterdam, Netherlands, Elsevier, 2015, pp. 479-522.

[24] USEPA, "Particulate matter (PM) pollution — Health and environmental effects of particulate matter (PM)," 2020.

[25] INEI, "Perú: Estimaciones y proyecciones de población por departamento, provincia y distrito 2018-2020," *Instituto Nacional de Estadística e Informática (INEI)*, Lima, 2020

[26] IQAIR, "World air quality report region & city 2.5 ranking," *IQAir AirVisual*, 2018.

[27] B. N. Vu, O. Sánchez, J. Bi, Q. Xiao, N. N. Hansel, W. Checkley, G. F. Gonzales, K. Steenland, and Y. Liu, "Developing an advanced PM2.5 exposure model in Lima, Peru," *Remote Sensing*, vol. 11, p. 1–18, 2019.

[28] W. Reátegui-Romero, W. Zaldivar-Alvarez, S. Pacsi-Valdivia, O. Sánchez-Ccoyllo, A. García, and A. Moya, "Behavior of the average concentrations as well as their PM10 and PM2.5 variability in the metropolitan area of Lima, Peru: Case study February and July 2016," *International Journal of Environmental Science and Development*, vol. 12, pp. 204-2013, 2021.

[29] J. Silva, J. Rojas, M. Norabuena, C. Molina, R. Toro, and M. Leiva, "Particulate matter levels in a South American megacity: the metropolitan area of Lima-Callao, Peru," *Environmental Monitoring Assess*, vol. 189, pp. 1-18, 2017.

[30] O. Sánchez-Ccoyllo, C. Ordoñez-Aquino, Á. Muñoz, A. Llacza, M. Andrade, Y. Liu, W. Reátegui-Romero, and G. Brasseur, "Modeling study of the particulate matter in lima with the WRF-chem model: Case study of april 2016," *International Journal of Applied Engineering Research*, vol. 13, pp. 10129-10141, 2018.

[31] V. Tapia, K. Steenland, S. Sarnat, B. Vu, Y. Liu, O. Sánchez-Ccoyllo, V. Vasquez, and G. Gonzales, "Time-series analysis of ambient PM2.5 and cardiorespiratory emergency room visits in Lima, Peru during 2010–2016," *Journal of Exposure Science & Environmental Epidemiology*, vol. 30, pp. 680-688, 2020.

[32] V. Barzeghar, P. Sarbakhsh, M. Hassanvand, S. Faridi, and A. Gholampour, "Long-term trend of ambient air PM_{10}, $PM_{2.5}$, and O_3 and their health effects in Tabriz city, Iran, during 2006–2017," *Sustainable Cities and Society*, vol. 54, p. 101988, 2020.

[33] F. B. Asl, M. Leili, Y. Vaziri, S. Arian, A. Cristaldi, G. Conti, and M. Ferrante, "Health impacts quantification of ambient air pollutants using AirQ model approach in Hamadan, Iran," *Environmental Research*, vol. 161, pp. 114-121, 2018.

[34] M. Miri, Z. Derakhshan, A. Allahabadi, E. Ahmadi, G. O. Conti, M. Ferrante, and H. E. Aval, "Mortality and morbidity due to exposure to outdoor air pollution in Mashhad metropolis, Iran. The Air Q model approach," *Environmental Research*, vol. 151, pp. 451-457, 2016.

[35] M. Miri, A. Alahabadi, H. Ehrampush, A. Rad, S. Lotfi, H. Mohammad, and Z. Sakhvidi, "Mortality and morbidity due to exposure to ambient particulate matter," *Ecotoxicology and Environmental Safety*, vol. 165, pp. 307-313, 2018.

[36] S. Faridi, M. Shamsipour, M. Krzyzanowski, N. Künzli, H. Amini, F. Azimi, M. Malkawi, F. Momeniha, A. Gholampour, M. Hassanvand, and K. Naddafi, "Long-term trends and health impact of PM2.5 and O3 in Tehran, Iran, 2006–2015," *Environment International*, vol. 114, pp. 37-49, 2018.

[37] H. Luo, Q. Guan, J. Lin, Q. Wang, L. Yang, Z. Tan, and N. Wang, "Air pollution characteristics and human health risks in key cities of northwest China," *Journal of Environmental Management*, vol. 269, p. 110791, 2020.

[38] L. Ferrero, A. Riccio, B. Ferrini, L. D'Angelo, G. Rovelli, M. Casati, F. Angelini, F. Barnaba, G. Gobbi, M. Cataldi, and E. Bolzacchini, "Satellite AOD conversion into ground PM10, PM2.5 and PM1 over the Po valley (Milan, Italy) exploiting information on aerosol vertical profiles, chemistry, hygroscopicity and meteorology," *Atmospheric Pollution Research*, vol. 10, pp. 1895-1912, 2019.

[39] N. Karimi, S. Namdari, A. Sorooshian, M. Bilal, and P. Heidary, "Evaluation and modification of SARA high-resolution AOD retrieval algorithm during high dust loading conditions over bright desert surfaces," *Atmospheric Pollution Research*, vol. 10, pp. 1005-1014, 2019.

[40] S. Kharol, K. Badarinath, A. Sharma, D. Kaskaoutis, and H. Kambezidis, "Multiyear analysis of Terra/Aqua MODIS aerosol optical depth and ground observations over tropical urban region of Hyderabad, India," *Atmospheric Environment*, vol. 45, pp. 1532-1542, 2011.

[41] USEPA, "IO Compendium Method IO-3.4. Determination of metals in ambient particulate matter using inductively coupled plasma (ICP) spectroscopy," *Cincinnati*, 1999.

[42] USEPA, "Compendium Method IO-2.1. Sampling of ambient air for total suspended particulate matter (SPM) and PM10 using High Volume (HV) sampler," *Cincinnati*, 1999.

[43] L. González, F. Longoria-Rodríguez, M. Sánchez-Domínguez, C. Leyva-Porras, K. Acuña-Askar, B. Kharissov, A. Arizpe-Zapata, and J. Alfaro-Barbosa, "Seasonal variation and chemical composition of particulate matter: A study by XPS, ICP-AES and sequential microanalysis using Raman with SEM/EDS," *Journal of Environmental Sciences*, vol. 74, pp. 32-49, 2018.

[44] B. Khalid, A. Khalid, S. Muslim, A. Habib, K. Khan, D. Souza, S. Shakoor, S. Mustafa, S. Zaheer, M. Zoon, A. Hayat, S. Ilyas, and B. Chen, "Estimation of aerosol optical depth in relation to meteorological parameters over eastern and western routes of China Pakistan economic corridor," *Journal of Environmental Sciences*, vol. 99, pp. 28-39, 2021.

[45] K. Alam, S. Qureshim and T. Blaschke, "Monitoring spatio-temporal aerosol patterns over Pakistan based on MODIS, TOMS and MISR satellite data and a HYSPLIT model," *Atmospheric Environment*, vol. 45, pp. 4641-4651, 2011.

[46] WHO, "AirQ+: software tool for health risk assessment of air pollution," World Health Organization (WHO), Geneva, 2021.

[47] J. Rovira, J. Domingo, and M. Schuhmacher, "Air quality, health impacts and burden of disease due to air pollution (PM10, PM2.5, NO2 and O3): Application of AirQ+ model to the Camp de Tarragona County (Catalonia, Spain)," *Science of the Total Environment*, vol. 703, p. 135538, 2020.

[48] M. Héroux, H. Anderson, R. Atkinson, B. Brunekreef, A. Cohen, F. Forastiere, F. Hurley, K. Katsouyanni, D. Krewski, M. Krzyzanowski, N. Kunzli, I. Mills, X. Querol, B. Ostro, and H. Walton, "Quantifying the health impacts of ambient air pollutants: Recommendations of a WHO/Europe project," *International Journal of Public Health*, vol. 60, pp. 619–627, 2015.

[49] F. Islam, S. Sanjida, A. Mamun, B. Khan, M. Arifur, and A. Salam, "Trace metals concentrations at the atmosphere particulate matters in the Southeast Asian Mega City (Dhaka, Bangladesh)," *Open Journal of Air Pollution*, 2015, vol. 4, pp. 86-98, 2015.

[50] B. Alharbi, M. Mujtaba, and T. Husain, "Study of chemical characteristics of particulate matter concentrations in Riyadh, Saudi Arabia," *Atmospheric Pollution Research*, vol. 6, pp. 88-98, 2015.

[51] J. Cardoso, M. Almeida, T. Nunes, M. Almeida, M. Cerqueira, C. Alves, F. Rocha, P. Chaves, M. Reis, P. Salvador, B. Artiñano, and C. Pio, "Source apportionment of atmospheric aerosol in a marine dusty environment by ionic/composition mass balance (IMB)," *Atmospheric Chemistry and Physics*, vol. 18, pp. 13215 -12230, 2018.

[52] M. Singh, P. Jaques, and C. Sioutas, "Size distribution and diurnal characteristics of particle-bound metals in source and receptor sites of the Los Angeleles Basin," *Atmospheric Environment*, vol. 36, pp. 1675-1689, 2002.

[53] K. Singh, S. Gupta, S. Ramteke, K. Prakash, S. Nava, and F. Lucarelli, "Silica particulate pollution in Central India," *Journal of Environmental Protection*, vol. 7, pp. 170-175, 2016.

[54] D. Dahmann, D. Taeger, M. Kappler, S. Büchte, P. Morfeld, T. Brüning, and B. Pesch, "Assessment of exposure in epidemiological studies: The example of silica dust," *Journal of Exposure Science and Environmental Epidemiology*, vol. 8, pp. 452-461, 2008.

[55] E. Lynge, K. Kurppa, L. Kristofersen, H. Malker, and H. Sauli, "Silica dust and lung cancer: Results from the nordic occupational mortality and cancer incidence registers," *Journal of the National Cancer Institute*, vol. 99, pp. 883-889, 1986.

[56] GEA, "Measurement of sea salt aerosol in Gibraltar Quantification of the contribution of sea salt to the total airborne ambient PM10 mass concentration," Gibraltar Environmental Agency, Gibraltar, 2012.

[57] A. Salam, M. Assaduzzaman, M. Nobi, and A. Alam, "Water soluble ionic species in the atmospheric fine particulate matters (PM2.5) in a Southeast Asian Mega City (Dhaka, Bangladesh)," *Open Journal of Air Pollution*, vol. 4, pp. 99-108, 2015.

[58] N. Opdyke and J. Channell, "Magnetic stratigraphy — Magnetization processes and magnetic properties of sediments," *International Geophysics*, vol. 64, San Diego, USA., Academic Press, 1996, pp. 26-48.

[59] A. Scheinost, "Metal oxides," *Encyclopedia of Soils in the Environment*, New York, USA, Elsevier, 2005, pp. 428-438.

[60] G. Cressey, "Minerals | Sulphates," *Encyclopedia of Geology*, Amsterdam, Academic Press, 2005, pp. 572-573.

[61] V. Vouk and W. Piver, "Metallic elements in fossil fuel combustion products: Amounts and combustion products: Amounts and of carcinogenicity and mutagenicity," *Environmental Health Perspectives*, vol. 47, pp. 201-225, 1983.

[62] R. Ruch, H. Gluskoter, and N. Shimp, "Occurrence and distribution of potentially volatile trace elements in coal — Illinois geological survey," *Environmental Geology*, no. 72, pp. 4-56, 1974.

[63] K. Shah, R. Filby, and W. Haller, "Determination of trace elements in petroleum by neutron activation analysis," *Journal of Radioanalytical Chemistry*, vol. 6, pp. 185–192, 1970.

[64] B. Zeb, K. Alam, A. Sorooshian, T. Blaschke, I. Ahmad, and I. Shahid, "On the morphology and composition of particulate matter in an urban environment," *Aerosol and Air Quality Research*, vol. 18, p. 1431–1447, 2018.

[65] R. Miranda, M. Andrade, A. Worobiec, and R. Grieken, "Characterisation of aerosol particles in the São Paulo Metropolitan area," *Atmospheric Environment*, vol. 36, pp. 345-352, 2020

[66] H. Al-Shidi, H. Sulaiman, and S. Alrubkhi, "Mass concentration and morphological analysis of PM10 and PM2.5 particles in congested roads during day hours in three major cities of Oman," *International Journal of Environmental Health Research*, pp. 1-14, 2020.

[67] P. Gupta, M. Satsangi, G. Satsangi, A. Jangid, Y. Liu, S. Pani, and R. Kumar, "Exposure to respirable and fine dust particle over North-Central India: Chemical characterization, source interpretation, and health risk analysis," *Environmental Geochemistry and Health*, vol. 42, pp. 2081–2099, 2020.

[68] G. Ali, Y. Bao *et al.*, "Spatiotemporal trends of aerosols over urban region in Pakistan and their possible links to meteorological parameters," *Atmosphere*, vol. 11, p. 306, 2020.

[69] P. Amoatey, P. Sicard, A. Marco, and Y. Khaniabadi, "Long-term exposure to ambient PM2.5 and impacts on health in Rome, Italy," *Clinical Epidemiology and Global Health*, vol. 8, pp. 531-535, 2020.

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