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Perspective

Aerosols as Vectors for Contaminants: A Perspective Based on Outdoor Aerosol Data from Kuwait

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Abstract: The Middle East is a hot spot of dust, and there are reports of as much as 1400 μg m^{-3} of dust in aerosols from Kuwait, which is among some of the highest dust loadings globally. A significant volume of literature has emerged on dust–air-quality–human-health, and the World Health Organization in its recent air quality guidelines has lowered the limit of annual $PM_{2.5}$ exposure to 5 μg m^{-3} from the previous limit of 10 μg m^{-3}. We present a mini-review based on a screening and search of the published data generated in Kuwait on contaminants associated with dust in different size fractions. We also include an unpublished study on organic contaminants in size-fractionated aerosols. The ΣPAHs concentrations in all the six size fractions range between 570 and 3350 pg m^{-3}. The ∑PBDE concentration ranges from ~2 to 1307 pg m^{-3}. The average ^{210}Po activity in aerosol size classes varies between 2289 and 2581 Bq kg^{-1}. The average ^{210}Pb concentration varies between 352 and 412 Bq kg^{-1}. The MP inventory in Kuwait's outdoor aerosol is between 5 and 35 MP in 815 ± 5 m^3 of air. The bacterial load in outdoor aerosols is between 6.05 × 10^3 cells m^{-3} and 1.24 × 10^8 cells m^{-3}. The fungal load ranges between 2.11 × 10^2 cells m^{-3} and 2.66 × 10^6 cells m^{-3}. The data suggest that the inhalable fraction of <2.5 μm size contains high concentrations of Polycyclic Aromatic Hydrocarbons (PAHs), Polybrominated diphenyl ethers (PBDEs), ^{210}Po, ^{210}Pb, microplastics, and microbes. These enriched ultrafine aerosols pose a significant risk to human health. The review also highlights the scarcity of contaminant data in respirable and inhalable size fractions that are critical for a comprehensive inhalation risk assessment.

Keywords: size-fractionated; aerosol; $PM_{2.5}$; PAHs; PBDEs; ^{210}Po; microplastics

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1. Introduction

A plethora of literature on air quality and particulate matter in aerosols is available. Particulate matter (PM) is designated as an air pollutant, with most countries providing guidelines on PM_{10} and $PM_{2.5}$ concentrations in indoor and outdoor aerosols. The World Health Organization (WHO) updated its Air Quality Guidelines (AQG) in September 2021 [1]. The updated guidelines of the WHO offer quantitative recommendations for air quality from a human health perspective, more explicitly dealing with the concentration–response function for $PM_{2.5}$, PM_{10}, ozone (O_3), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO) for relevant averaging times. The WHO carefully suggests these particulate contaminants have higher worldwide importance and relevance than other air pollutants. The WHO guidelines also touch on good practices for black carbon and elemental carbon, and ultra-fine particles from dust storms, stating that due to insufficient information, their risk assessment is not possible.

The new WHO AQG limit of 5 μg m^{-3} on annual $PM_{2.5}$ exposure is significantly reduced from the previous 10 μg m^{-3}. This is probably the result of the overwhelmingly large volume of literature citing health considerations from the inhalation of fine particulate matter [2]. One study has suggested that over 90% of the world's population is exposed to $PM_{2.5}$ concentrations >5 μg m^{-3} [3]. The particulate matter in aerosols will further exacerbate with climate change forcings, such as aridity, change in precipitation patterns, and forest fires, resulting in higher atmospheric dust loadings. Pai et al. [3] suggested that even without anthropogenic emissions, over half of the world's population would still experience annual $PM_{2.5}$ exposures >5 μg m^{-3}.

Dust storm episodes are recurrent weather phenomena in arid countries [4–12]. There are a few studies carried out in Asia, North America, and the Middle East that have addressed the impact of dust storms on human health [13–23]. The high-energy winds erode the topsoil in regions with minimal vegetation cover, resulting in very high PM. The Gulf Cooperation Council (GCC) region experiences some of the worst dust storms globally. Most GCC countries, including Kuwait, generally have a low topography, scant vegetative cover, very low precipitation, and strong winds during the summer months, resulting in very high PM in aerosols [24]. Mean monthly dust concentrations in Kuwait are as high as 1400 μg m^{-3}, one of the world's highest [25]. The frequency and intensity of the aerosol loadings are related to long- and short-term climate changes [26,27] and the modulation of air temperatures due to the scattering and absorption of solar radiation [28–32]. In addition, the size and type of aerosol significantly influence the radiation, in addition to cloud cover and surface albedo. Heavy dust storms have been reported to lower ocean temperatures, affecting the primary productivity of seas and oceans [33] and impacting carbon dioxide sequestration [33]. Several reports have indicated that dust serves as a vehicle for the long-range transport of associated contaminants, including viruses [34–37], pathogens [38], trace metals [39], and organic pollutants [39].

This communication emphasizes that the regulatory and advisory guidelines issues so far are mainly on the concentration of smaller size fractions, i.e., particulate matter of 2.5 μm sizes. Still, no guidelines exist on the allowable concentration of various pollutants in $PM_{2.5}$. The health implications associated with long-term exposure to PM linked to cardiovascular disease [21,40], chronic respiratory illnesses, and cancer need to consider the concentration of various contaminants in the inhalable size fraction. To better understand the risks posed by particle inhalation, it is vital to understand the distribution of pollutants in the various particle size fractions, especially the inhalable fraction. This communication demonstrates that significant amounts of radionuclides, POPs (PAHs, PBDE, PCDD/Fs) [41,42], MPs [43], and microbes are associated with inhalable fractions, and they are likely to result in very different health effects. Several of these contaminants such as ^{210}Po and ^{210}Pb, are highly particle-reactive and attach to aerosols within 40–180 s of their formation [44]. POPs, due to their semi-volatile nature, exist both as gases and are particle-bound, but due to their hydrophobic nature, they have a high affinity to organic matter [45]. The microbes in aerosols, absorb and adsorb organic and inorganic contaminants, acting as a potent vector, whereas MPs only adsorb a fraction of various contaminants. In the Gulf region, these contaminants are mostly scavenged due to dry deposition as rainfall is very low in this hyper-arid region. Hence, it is of paramount importance that each of these contaminants be properly accounted for, for a more realistic inhalation risk assessment. This study presents a synthesis and evidences on size-fractionated contaminants in atmospheric aerosols, which are reported to have a significant effect on human health [46–53].

2. Radionuclides

Polonium (^{210}Po, $T_{1/2}$ = 134 d) and radioactive lead (^{210}Pb, $T_{1/2}$ = 22.2 a) are naturally occurring radionuclides belonging to the uranium radioactive decay series. Their presence in the atmosphere is primarily due to the radioactive decay of radon gas (^{222}Rn; $T_{1/2}$ = 3.8 d) [54]. Due to the particle-reactive nature of ^{210}Po, it tends to attach to aerosol particles within 40 to 180 s after its formation [55]. The wet and dry atmospheric depositions

result in the scavenging of radon daughter nuclides from attaining secular equilibrium, resulting in background ^{210}Po/^{210}Pb ratios of ~0.1 [56].

In a study carried out in Kuwait, 24 h integrated aerosol samples were collected at two sampling sites, one near the Kuwait–Iraq border set within the Abdalli agricultural area away from any industrial operations regarded as a remote site, and the second in Kuwait City within the premises of the Kuwait Institute for Scientific Research considered as an urban site. An average volume of 815 ± 5 m^3 of aerosols was collected using High-Volume Air Samplers (HVAS) equipped with a six-stage cascade impactor (Tisch Environmental Inc.). The site, sampler, sampling substrate, and methodological details have been described elsewhere [57].

The samples were analyzed in three size fractions, i.e., >10 µm ($PM_{>10}$), 2.5–10 µm ($PM_{2.5–10}$), and 0.39–2.5 µm ($PM_{0.39–2.5}$). The average aerosol mass and load at the remote site were 0.9322 ± 0.5405 g and 0.1690 to 2.4733 mg/m^3, respectively; while at the urban site, they were 1.0086 ± 0.5368 g and 0.3064 to 2.5653 mg/m^3, respectively. The percentage of organic matter (dry) in the aerosols was also comparable, representing 15 ± 3 % at the remote site and 13 ± 1% at Kuwait city.

The average ^{210}Po activity in aerosol size classes varies between 2289 and 2581 Bq kg^{-1} (Figure 1) (Supplementary Table S1). There was no significant spatial and temporal difference in ^{210}Po concentration in aerosols in three particulate size classes.

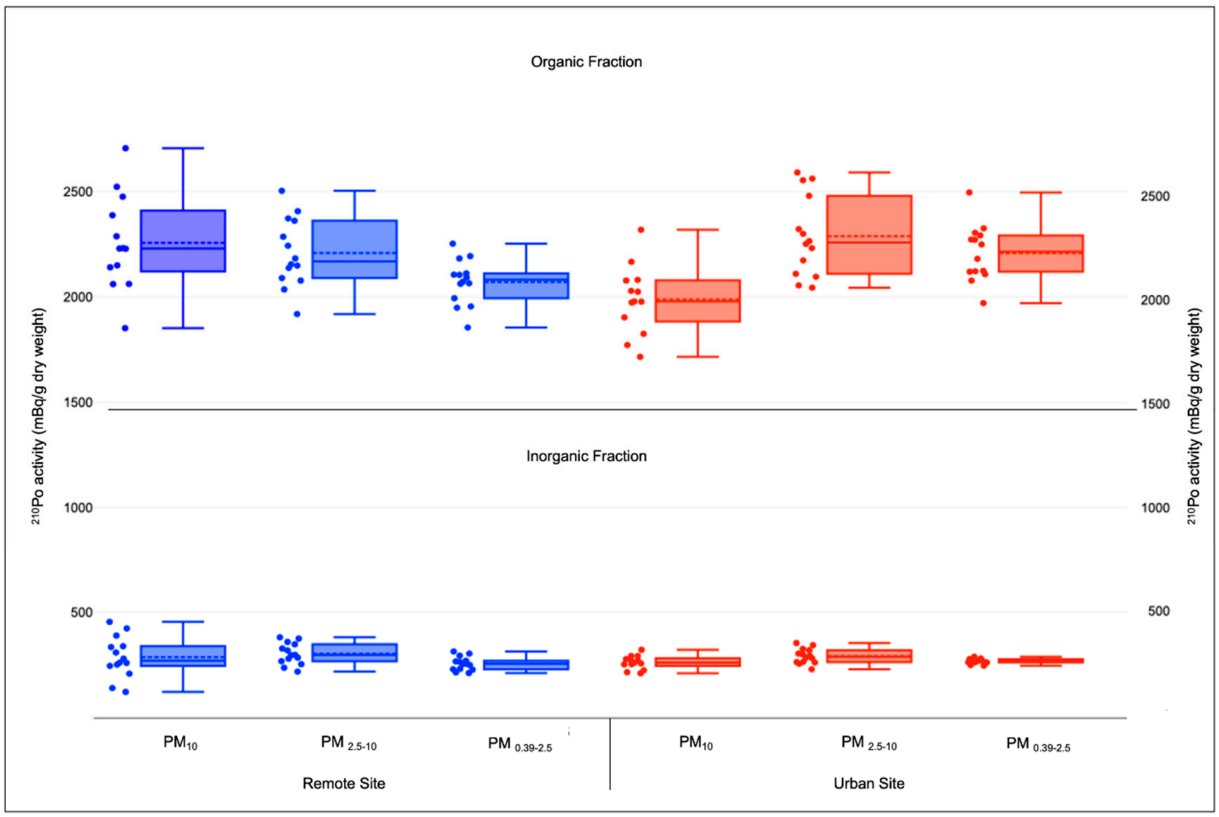


Figure 1. ^{210}Po activity in size-fractionated aerosol samples collected from remote, urban, and industrial sites in Kuwait [57].

In another study, aerosol samples were collected from the three sites including the remote site north of Kuwait City in Abdalli agriculture area, Kuwait city, and an industrial site that covers locations downwind of the refineries in the south. Specific activities of ^{210}Po were determined in 0.39–2.5 µm, 2.5–10 µm, and ≥10 µm size fractions during January 2018–November 2019 [58]. The ^{210}Po in $PM_{\geq 10}$ varied between 120 and 410 Bq kg^{-1} and those in $PM_{2.5–10}$ and $PM_{0.39–2.5}$ µm varied between 190 and 450 Bq kg^{-1} and 440 and 960 Bq kg^{-1}, respectively. The ^{210}Po concentration shows a spatial and temporal variability

in each of the three size fractions (Figure 2). The authors reported a reasonably higher ^{210}Po concentration downwind of the industrial site. The ^{210}Po concentrations at this site were 288–301 Bq kg^{-1} during winter and 370–406 Bq kg^{-1} during summer in $PM_{\geq 10}$, while in the $PM_{2.5–10}$ size fraction, the observed concentrations were 330–335 Bq kg^{-1} and 411–447 Bq kg^{-1} in winter and summer, respectively. The highest ^{210}Po concentration was measured in the $PM_{0.39–2.5}$ size fraction, with wintertime concentrations in the range of 855–863 Bq kg^{-1}, increasing to 916–944 Bq kg^{-1} during the summer season.

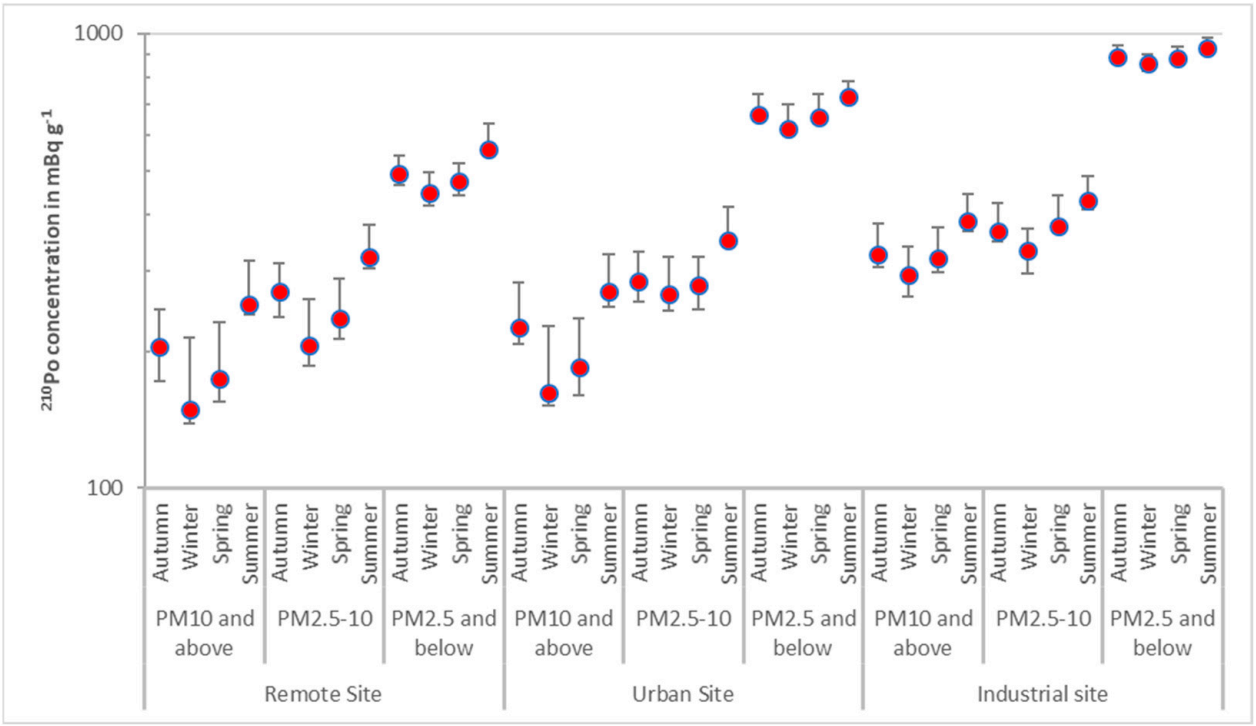


Figure 2. ^{210}Po activity in size-fractionated aerosol samples collected from remote, urban, and industrial sites in Kuwait [58].

In addition to atmospheric radon, a substantial quantity of ^{210}Pb and ^{210}Po comes from industrial activities, volcanic activity, forest fires, and fossil fuel combustion into the atmosphere [59–65]. The inhalation dose from ^{210}Po is very high, i.e., 2.2 µSv/Bq [66]. Studies have indicated that most ^{210}Po activity is associated with fine and ultrafine aerosol particles. Over 70% of ^{210}Po in aerosols was associated with the <0.7 µm size fraction in Japan [67]. In Poland, 82% of ^{210}Po in aerosols was measured in the particle size class fraction of 0.1–0.3 µm, while 8 to 30% of ^{210}Po was measured in the size class fraction less than 0.1 µm and was primarily attributed to emissions from industrial sources [68]. In forest fires in Portugal, most ^{210}Po in the aerosols was in <1 µm particles [62,63]. In Kuwait, ~91% of ^{210}Po was found in the 0.39–2.5 µm fraction [57,58,69].

In a study conducted by Behbehani et al. [57], it was found that 87–90% of ^{210}Po was associated with the organic matter in the aerosols, and this brings out an important discussion point that much of this polonium was associated with microbes in aerosols. Results for the ^{210}Pb activity concentrations in aerosols are shown in Figure 3 (Supplementary Table S2). At the two sampling stations, activity concentrations of ^{210}Pb in aerosols were comparable in the three size classes of particulates. A slightly higher ^{210}Pb in urban sites can be associated with the fossil fuel burning and industrial emissions.

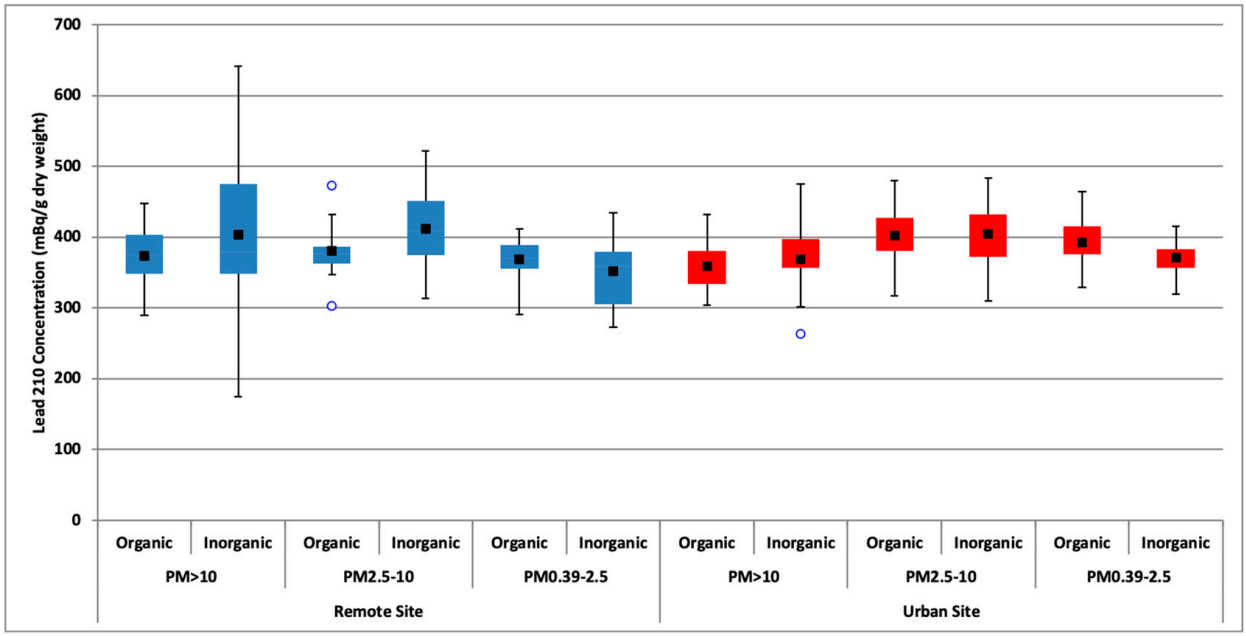


Figure 3. ^{210}Pb activity in size-fractionated aerosol samples collected from remote (R-blue-colored) and urban (U-red-colored) sites in Kuwait. The dotted lines and whiskers represent the STDEV, whereas the solid line shows the mean values after [70].

3. Organics

Biomass and fossil fuel burning are considered the two most important sources of aerosol primary organic particles, while secondary organic particles may originate from smog and combustible particles.

3.1. Polycyclic Aromatic Hydrocarbons (PAHs) Analyses

Polycyclic Aromatic Hydrocarbons (PAHs) are formed from both natural and anthropogenic sources, largely by the incomplete combustion of organic materials, such as wood, fossil fuels, asphalt, and industrial waste [71]. As PAHs are by-products of combustion, they have many current sources [72–75], including domestic burning, power generation, fossil fuel burning, and smoking. In a study carried out in Kuwait [23], the aerosol samples were collected from Abdalli (an agriculture area 120 km north of Kuwait city) and from Kuwait City. Using a high-volume air sampler, 815 ± 5 m^3 of air was passed through the filters in a six-stage cascade impactor and was separated into the following aerodynamic diameter (Dp) sizes ranges: <0.69 (backup high volume filter), 0.69 to 1.3, 1.3 to 2.1, 2.1 to 4.2, 4.2 to 10.2, and >10.2 µm. Prior to deployment, the filters were baked at 450 °C to thermally desorb any residual organic contaminants. Upon retrieval, the filters were individually weighed using a microbalance before and after the deployment to determine the amount of particles collected in each size range, which is nominally defined as the difference between the two measurements. The filters were then stored in separate cleaned aluminum foils in sealed Ziploc® bags and jars and maintained at −15 °C until extraction to minimize losses by both photolysis and volatilization. The size-fractionated particle concentration is provided in Figure 4.

All solvents used in this study were of analytical grade and purchased through VWR Scientific in New York (NY), United States of America (USA). Silica (100 to 200 mesh), alumina, and sodium sulfate manufactured by Baker in New Jersey, USA, were purchased through VWR Scientific (NY, USA). Deuterated PAH cocktail standard ES-2044 containing acenaphthylene-d_8, pyrene-d_{10}, phenanthrene-d_{10}, naphthalene-d_8, fluoranthene-d_{10}, benzo[*a*]pyrene-d_{12}, and benzo[*ghi*]perylene-d_{12} was used as the surrogate and was obtained from Cambridge Isotope Laboratories (CIL) in Andover, Massachusetts (MA), USA.

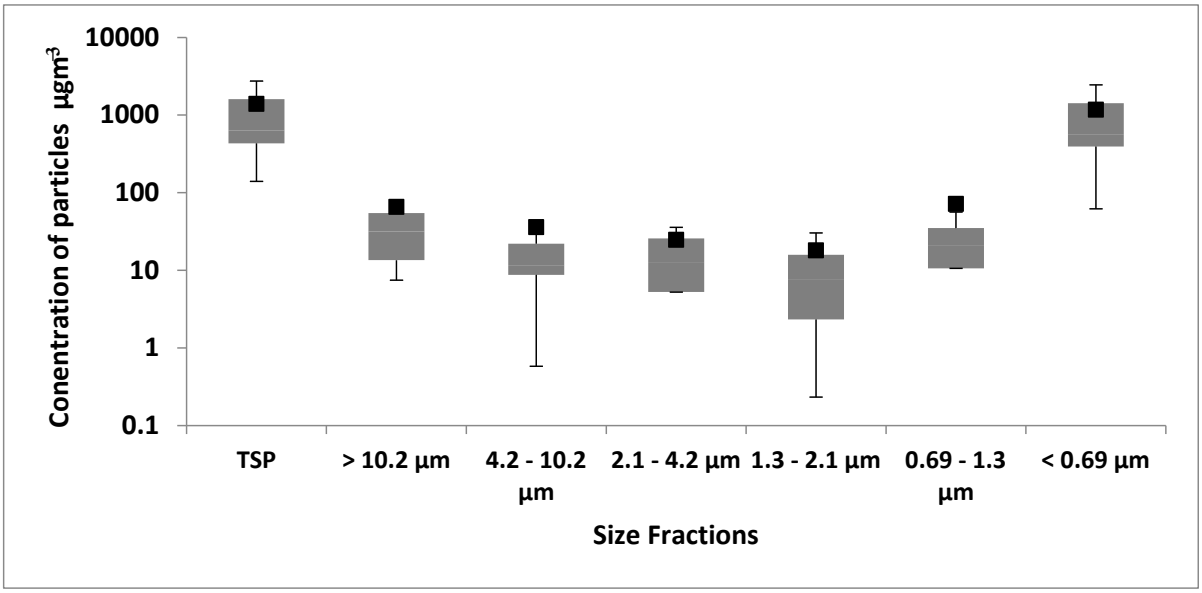


Figure 4. Atmospheric concentrations of particles in different size ranges and total suspended particulate concentration in the aerosol in Kuwait city between April and August 2012 after [23].

Individual filters were extracted in a Soxhlet apparatus using hexane. Prior to extraction, the samples were spiked with a range of deuterated PAH compounds (acenaphthene-d_{10}, anthracene-d_{10}, fluorene-d_{10}, chrysene-d_{12}, and perylene-d_{12}) to monitor analytical recovery. The extracts were reduced in volume on a Turbovap® *II* concentration workstation (obtained from Hopkinton, MA, USA), the solvent was exchanged to hexane, interfering compounds were removed by column chromatography using 2 g of silica and 1 g of alumina (and 0.5 cm of anhydrous Na_2SO_4 at the top of the column to prevent the column from contacting with air), and the compounds of interest were eluted with 40 mL 9:1 *v/v* of hexane:DCM. The eluent was blown down under a gentle stream of nitrogen, transferred to 2 mL vials, and blown down to a final volume of 500 µL. The samples were spiked with internal standard mirex (10 µL of 10 ng/µL) and used for volume correction and to adjust for variations in instrument response prior to chromatographic analysis.

The sample extracts were analyzed for PAHs using a Shimadzu GC-2010 (Shimadzu, Tokyo, Japan) gas chromatograph, which uses splitless injection (injection volume, 1 µL) on a 30 m DB5-ms column (0.25 mm i.d., 0.25 µm film thickness) and helium as a carrier gas. The oven program was set at 60 °C for 2 min, ramped from 20 °C min^{-1} to 180 °C, and further ramped at 6 °C min^{-1} to 280 °C and held for 20 min. The gas chromatograph was coupled to a Shimadzu 2010 Mass-Selective Detector, operated in electron impact (EI) mode using selected-ion monitoring (SIM). The injector temperature was set at 290 °C and the interface temperature at 280 °C. Identification and quantification were carried out against five calibration standards of known concentration using the internal standard method. Fifteen PAHs (acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benz[*a*]anthracene, chrysene, benzo[*b*]fluoranthene, benzo[*k*]fluoranthene, dibenz[*a,h*]anthracene, benzo[*a*]pyrene, indo [1,2,3-*cd*]pyrene, and benzo[*ghi*]perylene) routinely detected in samples were quantified. The sum of the concentrations of these PAHs was designated as ΣPAHs. Quality-assurance and quality-control measures were put in place to monitor the analytical process. Laboratory blanks comprised of baked filters were treated as samples. A peak was positively identified if it was within ±0.05 min of the retention time in the calibration standard and quantified only if $S/N \geq 3$ and the ratio of the target ion to its qualifier ion was within ±20% of the standard value. The analytes present in the appropriate blank were subtracted from those in the sample extracts. As some PAHs are known carcinogens, their concentrations were determined on the various size fractions (Figure 5).

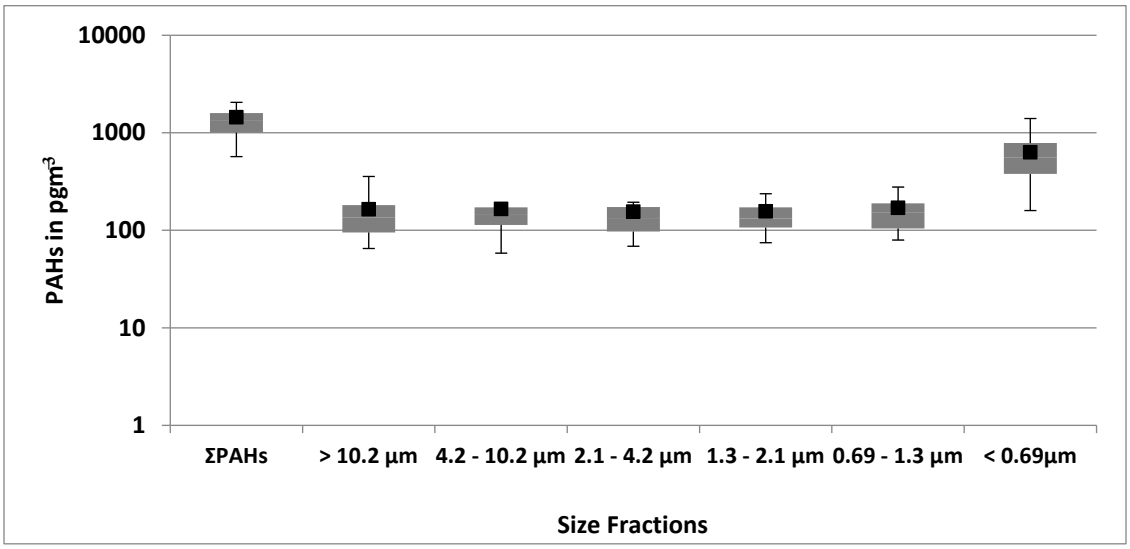
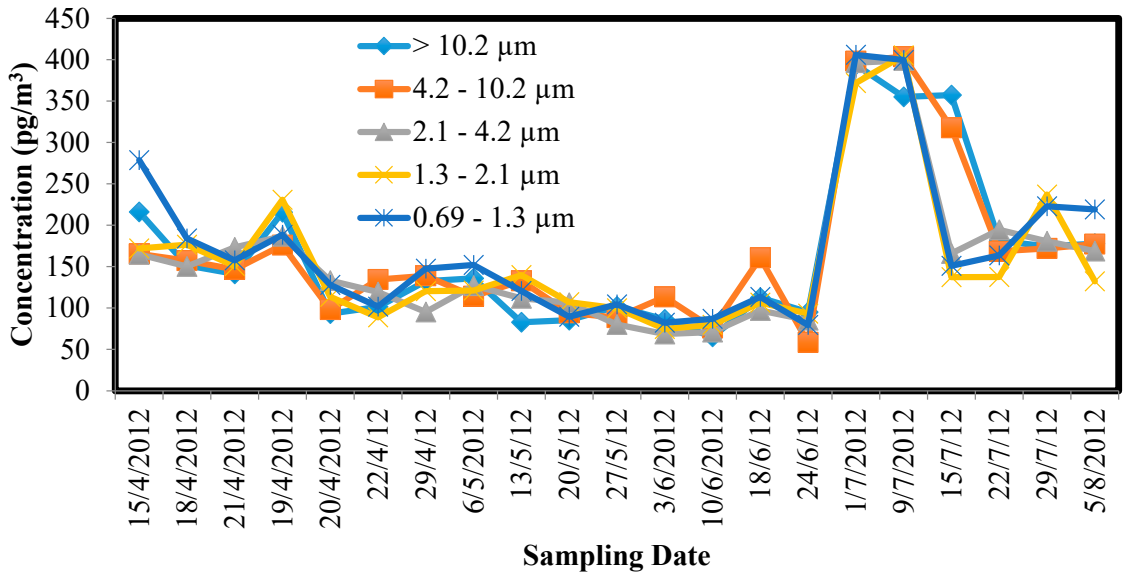


Figure 5. PAH concentrations in various size fractions measured between April and August 2012 in Kuwait city after [23].

The average concentrations of ΣPAHs over the study period in all the six size fractions were 1450 pg m^{-3} (range 570 to 3350 pg m^{-3}) (Figure 6). The PAH size distribution was unimodal, with the highest PAHs (average 46%, range 14 to 68%) measured in the <0.69 µm size range. This size-distribution data have been reported in several previous studies [75–79] and provide further evidence in support of the hypothesis that PAHs are mostly associated with fine particles in the respirable range. It has been hypothesized that PAHs are primarily emitted in the gaseous phase and as ultrafine particles in the atmosphere. This is particularly true for PAHs emitted from combustion sources [80]. As the aerosols age, it is thought that the PAHs in both the gas and/or ultrafine particles revolatilize and sorb onto larger or coarser particles. It is thought that the large particles can also be formed by condensation of smaller aerosols with time; therefore, the type of unimodal distribution observed in this, and other studies, may be due to the proximity to emission sources where the aerosol composition is relatively "young" [81].



(**a**)

Figure 6. *Cont.*

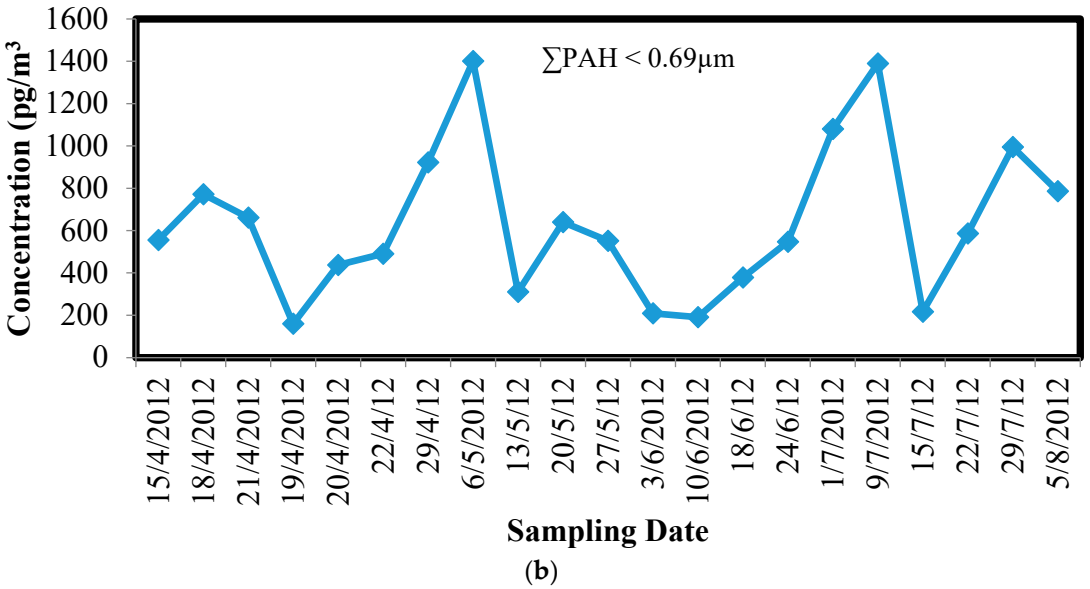


Figure 6. (**a**) ΣPAH concentrations in various size fractions measured between April and August 2012 in Kuwait city. (**b**) Concentrations of ∑PAHs in <0.69 µm size fraction between April and August 2012 in Kuwait city [23].

There are two peaks in the time series, the most prominent occurring between 24 June and the middle of July, with a smaller spike in concentration occurring toward the end of April and beginning of May 2012. These spikes in concentrations were not associated with increases in the TSP in the atmosphere. In fact, the concentrations of PAHs during the period of maximum TSP concentrations over the study period were one of the lowest. This observation appears to suggest that the sources of PAHs and dust are independent of one another. The causes of the spikes in the PAH concentrations over the periods mentioned above require further investigation.

3.2. Polybrominated Diphenyl Ethers (PBDEs)

Polybrominated diphenyl ethers (PBDEs) are hydrophobic contaminants that have a tendency to enter the gas phase and undergo long-range atmospheric transport [82–85]. PBDEs are widely used as flame retardant in a variety of electrical components, household appliances, furniture and furnishing, textiles, etc. [86,87]. The omnipresence of PBDEs and their propensity to bioaccumulate and cause harmful biological effects [88–90] have led to significant research and have been discontinued for use in consumer products as flame retardants. A study from Kuwait has reported levels of PBDEs during dust storms [91]. The ∑PBDE concentration of 51 to 1307 pg m^{-3} was reported on two days of a heavy dust storm and between 20 and 148 pg m^{-3} on three clear days following the storm in May 2007. The total suspended particulates (TSP) on dusty days exceeded 1000 µg m^{-3} with concentrations peaking during the day and decreasing at night. However, in this study, the dust-associated concentrations were not reported. The authors reported a significant diurnal fluctuation, with the peak nighttime ΣPBDE concentration 30 times higher than the minimum daytime concentration. This lower daytime ΣPBDE concentration was suggested to be a result of photolytic degradation [91].

3.3. Polychlorinated Dibenzo-p-Dioxin and Dibenzofuran (PCDD/F)

The polychlorinated dibenzo-p-dioxin and dibenzofuran (PCDD/F) are unintentionally produced persistent organic pollutants emitted from waste incineration, production of chlorinated compounds, and metal processing [89]. They have attracted significant interest due to the significant toxicity and carcinogenicity they can induce. A study from Kuwait reported PCDD/F from aerosol samples collected using a high-volume air sampler in

proximity to oil field operation between March 2014 and January 2015 [45]. The concentrations of ΣPCDD/Fs were between 33.6 and 586 fg I-TEQ m^{-3} with a median concentration of 94.7 fg I-TEQ m^{-3}. The authors linked these higher values to the oil desulfurization facility located in the study area and gas flaring in the oil fields that were upwind of the sampling location. In this study also, the authors did not quantify the amount of particulate matter in aerosols; however, they did report to have deployed a filter.

3.4. Microplastics in Aerosols

The ubiquitous presence of microplastics (plastics particles between 0.1 and 5 mm in size) in the aquatic environment [92–100] has attracted significant attention. It was only recently that scientists have started looking at microplastics (MPs) in aerosols [101–113]. The aerosols are a significant pathway for inhalation of MPs by humans [114–116]. The MPs get into aerosols from numerous sources, some of the most prominent ones of which are: plastic burned in landfills, wearing of clothing material [117–119], drying of synthetic clothes in dryers [120], the wear of synthetic rubber tires, deterioration of household furniture, and contamination from city dust [43,101,104–106,121,122]. Recent investigations have highlighted the need to standardize methodologies for MPs in aerosols for reliable inhalation exposure to humans [123,124].

Significant spatiotemporal variations in the concentration of MPs in aerosols have been reported. The MPs in the high-volume air samples were collected from Kuwait city and were between 5 and 35 MPs in 815 ± 5 m^3 of aerosol. The average MP inventory in aerosols from Paris varied between 53 and 110 MP m^{-2} day^{-1} [104,105] and 0.3 and 1.5 MP m^{-3} [106], compared to 275 MP m^{-2} day^{-1} in Hamburg [125] and 365 MP m^{-2} day^{-1} in the Pyrenees [103]; 175,602 particles m^{-2} day^{-1} in China [126,127] and 712 ± 162 particles m^{-2} day^{-1} in Central London [98,128]; 917 MPs m^{-2} day^{-1} in Vietnam [129], 0 to 30 MP m^{-2} day^{-1} in Gdynia, Poland [130]; 0.7 ± 1.5 to 11.7 ± 15.5 MP kg^{-1} in Badain Desert China [131].

In Indonesia, the West Pacific Ocean, Denmark, Ireland, Brazil, California, Shanghai (China), and Sydney, the concentrations were 132.75–174.97, 0–1.37, 1.67–16.2, 0–12, 0–24, 0.6–5.6, 0–4.18, and 12 MP m^{-3}, respectively [111,115,132–136]. In most studies conducted so far, the indoor MP concentrations are significantly higher than those outside [106,109,137,138].

In spite of several studies indicating inhalation of MPs leading to localized inflammation and genotoxicity among humans [108,111,139], the information on MPs in size-fractionated aerosols is very limited [124]. Few investigations have reported compromised respiratory functioning due to the presence of fibers in human lungs [140–144]. In one study, fibers were found in 99 of 114 malignant lung specimens [140], pointing toward the possible linkage between the presence of fibers and malignancy. There is growing information of the translocation of fine and ultrafine MPs into the human circulatory system and other organs [98,112,139,145]. The information on MP inventories in size-fractionated aerosols is scarce and the understanding of the pulmonary diseases from MP inhalation is even scarcer. The presence of over 4000 compounds in plastic manufacturing is well documented, and could these compounds lead to pulmonary toxicity, carcinogenicity, and mutagenicity [111,116,146,147]? The ability of MPs to act as a vector for contaminants has attracted the attention of researchers around the world [95,105,114,148–165]. Airborne MPs have been reported as a vector for transport of PAHs, pollutants from traffic emissions, and even microorganisms to the respiratory system, posing a potential threat to human health [166,167]. Another facet of MPs toxicity in aerosols is the release of plasticizers, frame retardants, Bisphenol A (BPA), and phthalates during MP degradation in the environment [168–171]. However, the magnitude of harm MPs in aerosols may cause to human health has not yet been well established [102,135,147].

4. Microbes

A considerable mass of the fine aerosols includes organic materials, such as hydrocarbons, microbes, and pollen. A significant fraction of the aerosol consists of living matter, such

as bacteria, fungi, pollen, and viruses, which are referred to as bioaerosols [172–176]. A few studies have reported the microbial load in urbanized aerosols from Kuwait [70,174,177]. The bacterial load in outdoor aerosols (10.8 m^{-3}) collected from an urban site with size fractions of >0.22 µm and <0.22 µm was between 6.05 × 10^3 cells m^{-3} and 1.24 × 10^8 cells m^{-3} with a mean concentration of 1.41 × 10^6 cells m^{-3}, and 7.92 × 10^5 cells m^{-3} and 1.05 × 10^8 cells m^{-3} with a mean concentration of 4.05 × 10^7 cells m^{-3}, respectively. Considering the average mass of one bacterium as 10^{-12} or 1 pg, the total mass of bacterial cells was higher in the smaller size fraction of <0.22 µm [70].

Fungal cell numbers ranged between 2.11 × 10^2 cells m^{-3} and 6.53 × 10^3 cells m^{-3} in the >0.22 µm size fraction, with a mean concentration of 1.66 × 10^3 cells m^{-3}, while in the <0.22 size fraction, the concentrations were between 8.40 × 10^3 cells m^{-3} and 2.66 × 10^6 cells m^{-3}, with a mean concentration of 1.34 × 10^6 cells m^{-3} (Figure 7) [70]. In another study, a 3.6 m^{-3} aerosol sample was collected in a residential area, where the bacterial load was between 2.90 × 10^4 and 6.09 × 10^4 cells m^{-3} [174,177], whereas the fungal cells were 1.97 × 10^3 cells m^{-3}. The bacterial cells were ubiquitous across the samples, while fungal cells were below the detection limit in many of the samples (Supplementary Table S3).

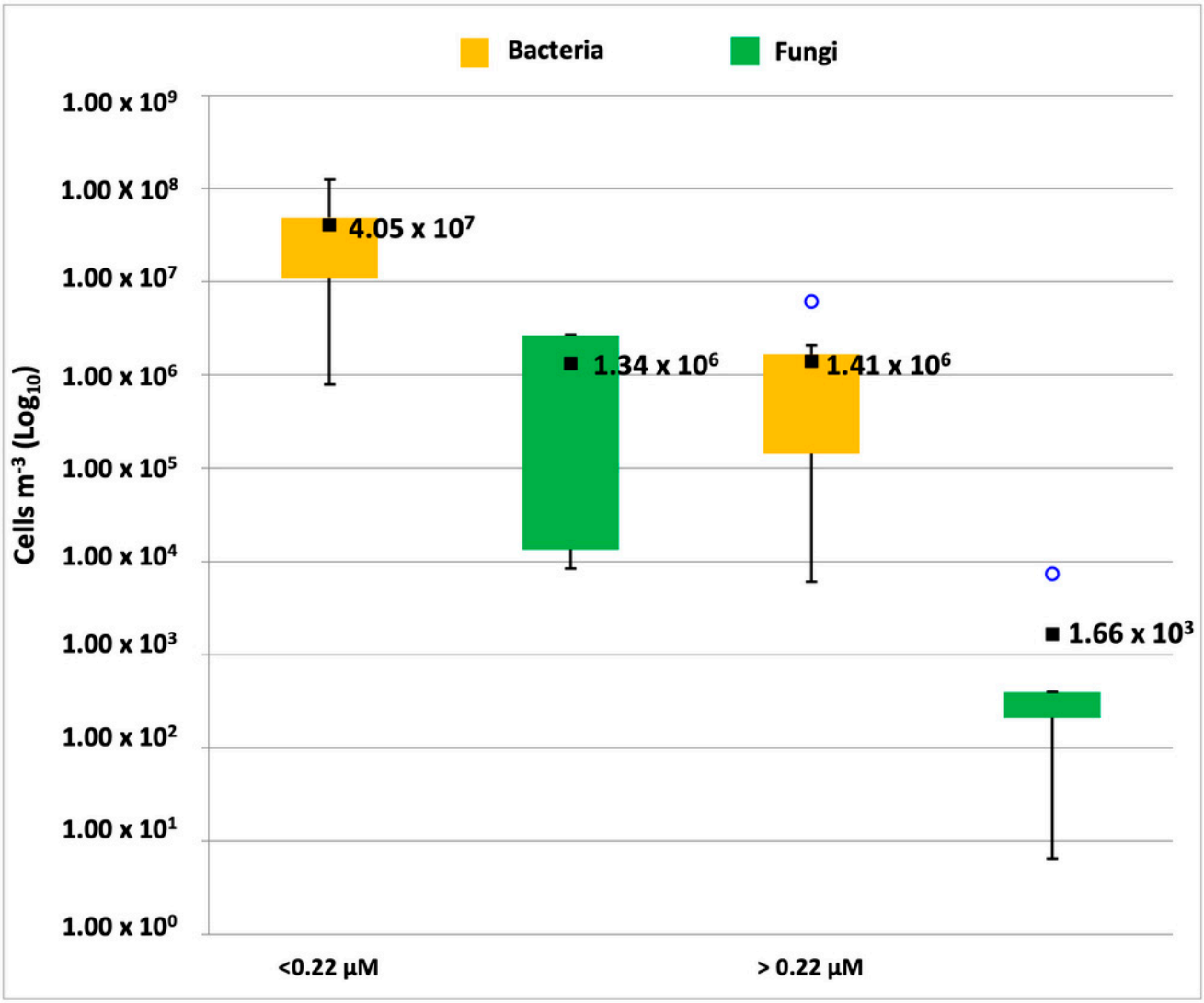


Figure 7. Bacterial and Fungal load in two size fractions of outdoor aerosols. The black dot in each box represents the average values and the blue circles are the outliers [70].

The relative abundances in different size fractions were also identified through the advanced molecular methods of reverse transcriptase polymerase chain reaction (RT-PCR) and next-generation sequencing (NGS) [70,174–181]. The presence of pathogenic microbes *Mycoplasma pneumonia*, *Moraxella catarhallis*, and *Legionella pneumophila* in the <0.22 µm size fraction [70] raises a human health concern and is likely to exacerbate pulmonary diseases.

Several studies were conducted in Kuwait to look at the microbial community associated with size-fractionated aerosols. The samples were collected using a high-volume air sampler, and the particulate matter was characterized in 0.39 to >10.2 µm size fractions. The microbial identification was conducted for respirable (>2.5–>10 µm) and inhalable (0.39–<2.5 µm) fractions using whole-genomic DNA, which was isolated using universal primers to map the entire bacterial and fungal community. Most of the aerosols in the respirable fraction reside in the upper respiratory tract, whereas the inhalable finer aerosols make their way into the pulmonary region where the air exchange takes place [174,177,178,180]. A total of 50 bacterial genera were distributed in the respirable fraction [176], with *Brevundimonas* typically present in >0.69 to 10.2 µm and *Massilia* dominating the >10.2 µm size range at the urban site. In the same study, *Sphingobium* exhibited its highest prevalence in the >4.2 to 10.2 µm range at the remote site. Contrastingly, Habibi et al. [179] reported 109 bacterial genera of which *Aeromonas* dominated in all the size fractions (0.39 to >10.2 µm) at the urban site. However, *Sphingobium* (> 1.3 to 10.2 µm) and *Brevundimonas* prevailed (>0.69 to 1.3 µm; >10.2 µm) in the respirable fraction at the remote site (Table 1). Although different bacterial types dominated in these two studies, all the bacterial genera were characteristic to the air habitat. Spatiotemporal variations in microbial profiles are a common phenomenon [175,176,182]. Many of the bacterial genera reported by both the studies were opportunistic pathogens and are known to have severe health implications upon inhalation.

Table 1. Predominant Bacteria identified in different size fractions of outdoor aerosols using different approaches in Kuwait.

	Size Fractions	NGS	NGS	Microscopic
Urban	0.39 to 0.69 µm	*Aeromonas*	<LOD	*Streptomyces, Bacillus*
	>0.69 to 1.3 µm	*Aeromonas*	*Brevundimonas*	
	>1.3 to 2.1 µm	*Aeromonas*	*Brevundimonas*	
	>2.1 to 4.2 µm	*Aeromonas*	*Brevundimonas*	*Bacillus*
	>4.2 to 10.2 µm	*Aeromonas*	*Brevundimonas*	
	>10.2 µm	*Aeromonas*	*Massilia*	
Remote	0.39 to 0.69 µm	*Brevundimonas*	<LOD	*Bacillus*
	>0.69 to 1.3 µm	*Aeromonas*	*Brevundimonas*	
	>1.3 to 2.1 µm	*Sphingobium*	*Brevundimonas*	
	>2.1 to 4.2 µm	*Sphingobium*	*Brevundimonas*	*Bacillus, Paenibacillus*
	>4.2 to 10.2 µm	*Sphingobium*	*Sphingobium*	
	>10.2 µm	*Brevundimonas*	*Brevundimonas*	

NGS: next generation sequencing

In one of the reports, the samples were collected on a medium to explore if any viable cells exist in the aerosol community (Table 1). Petri dishes filled with Nutrient agar media were placed in the six-stage Andersen cascade impactor and air was drawn at 30 L min^{-1} for 2 h. The air-laden Petri dishes were aseptically harvested and incubated at 30–37 °C for one week to allow the bacteria and fungi to grow. Single colonies were picked and serially diluted to obtain a pure culture. The isolates were visually examined under a microscope and identified through 16S rRNA sequencing [183]. Applying the culture-based approach, *Bacillus*, *Paenibacillus*, and *Streptomyces* were the metabolically active bacteria present in the inhalable and respirable fractions of outdoor aerosols [175]. These genera were recorded in very low abundances through the NGS method [176].

The assessment of fungal taxons revealed the presence of *Alternaria*, *Cryptococcus*, and *Aspergillus* in all the size fractions (>10.2–0.39 µm) [175,176]. *Alternaria* preceded the fungal community in the inhalable fractions collected from both the urban and the remote sites (Table 2). Several *Alternaria* species are known to cause infectious diseases in animals, humans, and plants. In yet another study (data not published), it was *Aspergillus* and *Alternaria* that were the most prevalent, with the latter exhibiting the highest relative abundance in the <0.69 µm size fraction at the remote site. While most of the fungal communities remained undetected in size fractions above 1.3 µm, *Bionectria* was found with higher abundances below 0.69 µm at the urban site. The culture-based approach identified two fungal species of *Fusarium coccidiocola* and *Aspergillus brasilensis* in both remote and urban locations of Kuwait [175].

Table 2. Predominant Fungi identified in different size fractions of outdoor aerosols in Kuwait.

	Size Fractions	NGS	NGS	Microscopic
Urban	0.39 to 0.69 µm	*Alternaria*	*Bionectria*	*Fusarium coccidiocola*
	>0.69 to 1.3 µm	*Cryptococcus*	*Bionectria*	
	>1.3 to 2.1 µm	*Cryptococcus*	<LOD	
	>2.1 to 4.2 µm	*Cryptococcus*	<LOD	*Aspergillus brasilensis*
	>4.2 to 10.2 µm	*Cryptococcus*	<LOD	
	>10.2 µm	*Aspergillus*	<LOD	
Remote	0.39 to 0.69 µm	*Alternaria*	*Alternaria*	*Fusarium coccidiocola*
	>0.69 to 1.3 µm	*Cryptococcus*	*Alternaria*	
	>1.3 to 2.1 µm	*Schizophylum*	*Aspergillus*	
	>2.1 to 4.2 µm	*Alternaria*	*Aspergillus*	*Aspergillus brasilensis*
	>4.2 to 10.2 µm	*Aspergillus*	*Aspergillus*	
	>10.2 µm	*Cryptococcus*	*Aspergillus*	

NGS: Next-generation sequencing

In addition to the bacterial and fungal genera, some viruses were also captured in the outdoor environment of Kuwait [70,177,181]. Viral identification in aerosols remains very challenging due to its nano-size and lower abundance as compared to bacteria and fungi. Only 0.05% of cDNA aligned to the viral primers used in comprehensive viral panel sequencing (CRVP), whereas 50–60% was identified as non-target DNA most likely to be originating from bacteria, fungi, and other higher eukaryotes [174,181]. To maximize the efficiency, a specialized sampling device was designed to collect the whole fraction of air [178]. This sampler had an added advantage of sampling and lysing the pathogenic microbes simultaneously, therefore minimizing the risk of cross-infection and transmission. The device was further improved to collect two size fractions of air (<0.22 µm and >0.22 µm) [70] in the belief that all the viruses will be passed to the <0.22 µm fraction. With this size-cutoff being lower than the lower limit of the inhalable fraction, i.e., 0.39 µm, the microbes residing within this fraction are likely to penetrate our pulmonary system. Through RT-PCR, respiratory viruses such as Enterovirus, Rhinovirus, FluA, Para Influenza 4, non-SARS coronavirus, HKU1, and OC43 were detected in the <0.22 µm size fraction of outdoor aerosols collected over a period of three months (February–May, 2021). In addition to all the above-mentioned viruses, Adenovirus, FluB, and SARS-CoV2 were also found in the size fraction of >0.22 µm. The same set of samples were pooled to perform CRVP sequencing, which discovered human bocavirus 1 at a higher depth in both size fractions. Several low-coverage viruses were also detected and are shown in Table 3. The types of viruses did not differ in both size fractions. All the viruses detected are known respiratory pathogens [177].

Table 3. Viruses detected in outdoor aerosols of Kuwait.

Size Fraction	Viruses	Method	References
<0.22 µm	Enterovirus, Rhinovirus, Flu A, Para Influenza 4, CoV-HKU1, CoV-OC43	RT-PCR	[70]
>0.22 µm	Adenovirus, Enterovirus, Rhinovirus, Flu A, Flu B, Para Influenza 4, CoV-OC43, SARS-CoV2	RT-PCR	
Whole fraction	Rhinovirus	RT-PCR	[174,177,180]
<0.22 µm	Human bocavirus 1, HAdV-C1, HAdV-C2, HAdV-B3, HAdV-E4, HAdV-C5, HAdV-B7, HAdV-B21, H1N1, SARS CoV2	CRVP sequencing	[182]
> 0.22 µm	Human bocavirus 1, HAdV-C1, HAdV-C2, HAdV-B3, HAdV-E4, HAdV-C5, HAdV-B7, HAdV-B21, H1N1, SARS CoV2	CRVP sequencing	

The bioaerosols have been associated with asthma, allergic reactions, infections, flu, respiratory illnesses, and toxicosis of the respiratory system in humans [6,16–18,184–187]. The bacterial meningitis in sub-Saharan Africa [188] and the Valley Fever outbreak in 1990s in the United States [189] were found to be associated with dust storm activity. Human and plant pathogenic bacteria were recorded during dust storms in the Virgin Islands and Mali (West Africa) [16,186], while dust-induced pneumonia was reported to occur among military personnel deployed in the Middle East [34,190]. Behbehani et al. [57] demonstrated the enrichment of atmospheric ^{210}Po in the organic phase of air-borne particulate matter by the inherent microbial communities.

It is also important to note that besides the dominant taxa, a good number of low-abundance bacterial, fungal, and viral genera and species (RA < 0.01%) are also present within an environment. Sogin et al. [191] coined the term rare biosphere for them and explained that their presence is of ecological significance. These genera and species are often overlooked, but the fact is that these might be the key components playing a role in disease dysbiosis. It is the entire microbial consortia that interact with other contaminants of the aerosols that form a hazardous state.

5. Discussion

The scientific community has emphasized the role of airborne dust in human health impacts and the climate. The Middle East region is one of the hotspots of dust due to its largely flat topography, low vegetation cover, and strong winds. The dust loadings in Kuwait are considered as one of the highest in the world, likely resulting in an enormous redistribution of contaminants associated with the dust. In this review, we have aimed to provide an overview of the various contaminants associated with dust and an insight into their levels in aerosols.

It is evident from the review of data that the region so heavily impacted by dust loadings lacks sufficient data to assess the extent to which aerosol-mediated contaminants can impact human health due to inhalation and dry ingestion. We have provided a review and presented some unpublished data from our studies conducted in the northwestern Gulf, to emphasize how little we know about the problem that the region has faced for decades. The limited studies on size-fractionated aerosols and associated contaminants ascertains a significant knowledge gap that needs to be addressed as it severely impacts the pulmonary health of the local population.

The WHO's updated AQG emphasizes air quality from a human health perspective specifically focusing on $PM_{2.5}$, PM_{10}, ozone (O_3), nitrogen dioxide (N_2O), sulfur dioxide (SO_2), and carbon monoxide (CO) and carefully proposes their higher importance and relevance while also suggesting the importance of other air pollutants [1]. The new WHO AQG limit of 5 µg m^{-3} on annual $PM_{2.5}$ exposure is a significant reduction from the previous limit of 10 µg m^{-3}. It is quite evident from studies that over 90% of the world's

population is exposed to $PM_{2.5}$ concentrations >5 μg m^{-3}, and even with no anthropogenic emissions, over half of the world's population would still experience annual $PM_{2.5}$ exposures >5 μg m^{-3}. Given the evidence of organic contaminants such as PAHs, PCBs, PBDEs, and PCDD/Fs in detectable levels in inhalable and respirable fractions of aerosols, more detailed human risk assessments are warranted.

The elevated levels of ^{210}Po and ^{210}Pb in the inhalable fraction raises substantial concern, particularly in oil-producing regions where the levels are similar to those reported during forest fires in other parts of the world. The ^{210}Po concentration was one to two orders of magnitude higher than those found in the topsoils [192]. The annual average $^{210}Po/^{210}Pb$ ratio in Kuwait is 1.5, significantly higher than the natural global background of 0.1.

The allergenic and pathogenic microbes associated with the fine and ultrafine particles in aerosols are also an issue of grave concern and these factors are often disregarded in risk assessments due to inhalation of dust.

The satellite-derived aerosol concentrations can help fill in the data gap on aerosol loadings especially on $PM_{2.5}$, at the national, regional, and global scale, as it is an established fact that dust serves as a vehicle for long-range transport of viruses, pathogens, trace metals, organic pollutants, and radionuclides. Global estimates of dust emissions, mainly derived from simulation models, vary between one and three Gigatons per year, with an average lifetime of dust particles in the atmosphere ranging from a few hours for particles with a diameter larger than 10 μm, to more than 10 days for the sub-micrometric particles. We have observed a similar trend in Kuwait where the $PM_{2.5}$ levels were higher after a dust storm and there was a lag of 6 to 48 h when the ultrafine fraction peaked after a storm, which should also be considered when issuing advisories; it is not only the visibility but the higher contaminant-laden inhalable fraction that might be more important for issuing health advisories.

6. Conclusions

Airborne dust presents significant human health risks, especially the ultrafine particles that reach the respiratory system and are known to cause ailments such as asthma, tracheitis, pneumonia, allergic rhinitis, and silicosis and may even penetrate the lower respiratory tract and enter the bloodstream, where they can affect all internal organs.

The data included in this paper and elsewhere show that the inhalable particles are an effective vector of pollutant transport and are often rich in organic pollutants, metals [193], radionuclides, microbes, and microplastics to name a few. Based on this consideration, it is not sufficient to determine only levels of $PM_{2.5}$ but also the chemicals associated with the particles to make a realistic health risk assessment.

The higher PAHs and PBDEs during dust storm events show the long-range transport of these chemicals along with dust, which might help in source appropriation. The higher ^{210}Po levels in Kuwait can be due to the emission of volatilized ^{210}Po from oil operations, followed by cooling and condensation onto aerosol particulates with the consequent enhancement in $^{210}Po/^{210}Pb$ ratios. The ^{210}Po results indicate that the enhancement of atmospheric ^{210}Po is not merely from a local point source but seems to be an enhancement rather at the regional scale and probably related to emissions from the entire oil industry around the Gulf.

The composition of aerosol particulates may include diversified materials from several origins, such as soil dust, pollen grains, fungi, microbes, soot, and black carbon from industrial emissions. The results of studies in Kuwait revealed the dominance of the phylum *Proteobacteria*. All these bacteria genera belong to both Gram-negative as well as to Gram-positive bacteria types and their outer membranes are mainly composed of lipopolysaccharides. It was established that bacteria, especially those involved in the sulfur (S) cycle, play a role in dissolution and mobilization of polonium. Fungal phyla were mainly dominated by *Ascomycota* (RA-), *Basidiomycota,* and *Zygomycota*. Fungi have long since been proven to be regulating the radionuclide movement in soils. No data are available on the

bioconcentration of ^{210}Po in microscopic fungi, but for macroscopic fungi (mushrooms) and also lichens, it is known that they concentrate ^{210}Po from soils and from air [18]. Likewise, microscopic fungi in aerosols can be expected to concentrate airborne ^{210}Po.

In spite of concerted efforts by the scientific community, there is a general lack of data on size-fractionated aerosols. This study has focused on the importance of not only the physical size but the chemistry of the fine and ultrafine particles that are likely to have a much more significant impact on human health. Such chemical characterization of fine aerosols is important from both a source identification and abatement point of view. Such detailed knowledge of fine particulates will also be more realistic to facilitate region-specific air quality management decisions and improve health-burden estimates of fine aerosol exposure to make a meaningful risk assessment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14030470/s1, Table S1: ^{210}Po activity concentration in size fractioned aerosol samples collected from Remote and Urban sites in Kuwait; Table S2: ^{210}Pb activity concentration in size fractioned aerosol samples collected from Remote and Urban sites in Kuwait; Table S3: Bacterial and Fungal load in outdoor aerosols.

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