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REVIEW ARTICLE

A review on the direct effect of particulate atmospheric pollution on materials and its mitigation for sustainable cities and societies

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Abstract

Particulate matter (PM) has gained significant attention due to the increasing concerns related to their effects on human health. Although several reviews have shed light on the effect of PM on human health, their critical adverse effect on material's structure and sustainability was almost neglected. The current study is an attempt to fill this gap related to PM impact on structural materials under the overall consideration of sustainability. More specifically, this review highlights the existing knowledge by providing an overview on PM classification, composition, and sources in different locations around the world. Then, it focuses on PM soiling of surfaces such as solar panels due to an increasing need to mitigate the impact of soiling on reducing photovoltaic (PV) power output and financial competitiveness in dusty regions. This topic is of critical importance for sustainable deployment of solar energy in arid and desert areas around the world to help in reducing their impact on overall climate change and life quality. In addition, this review summarizes climate change phenomena driven by the increase of PM concentration in air such as radiative forcing and acid rain deposition due to their impact on human health, visibility and biodiversity. To this end, this work highlights the role of process management, choice of fuel, the implementation of clean technologies and urban vegetation as some possible sustainable mitigation policies to control PM pollution in cities and urban regions. This research is designed to conduct a comprehensive narrative literature review which targets broad spectrum of readers and new researchers in the field. Moreover, it provides a critical analysis highlighting the need to fill main research gaps in this domain. The findings of this review paper show that PM pollution imposes severe adverse impacts on materials, structures and climate which directly affect the sustainability of urban cities. The advantages of this review include the value of the extensive works that elaborate on the negative impacts of PM atmospheric pollution towards high level of public awareness, management flexibility, stakeholder's involvements, and collaboration between academy, research, and industry to mitigate PM impact on materials and human welfare.

Keywords Air quality · Particulate matter · Atmospheric pollution · Materials · Soiling · Solar

Introduction

Airborne particulate matter, or more specifically atmospheric aerosols, has significant impact on climate change and atmospheric chemistry which reflects on the overall air quality and human health (Kampa and Castanas 2008; Rajšić et al. 2004; Dickerson et al. 2017; Fajersztajn et al. 2017; Anderson et al. 2012). The effect of aerosol particles on human health, ecosystem, climate, and outdoor materials has significantly increased from pre-industrial times to the present days (Jimoda 2012; Yin et al. 2011; Liang et al. 2016). The history of air quality management includes various examples of technological, social, and policy responses to pollution caused by particulate matter over years. During the Middle Ages in London, for instance, the frequent presence of soot and dust clouds led

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to the banning of coal burning (Bhattacharjee et al. 1999). Later on, air pollution related to particulate matter (PM) was managed at a local level as it was considered as a municipal problem rather than a public health issue during the Industrial Revolution and continued well into the twentieth century (Bhattacharjee et al. 1999). In the 1950s, federally funded research programs have been developed that lead to the establishment of the Clean Air Act and the Environment Protection Agency (EPA) in the USA in 1970 (Bhattacharjee et al. 1999). Recently, air quality degradation has been considered significantly due to the impact of dust and aerosol particles (Jimoda, 2012; Chow et al. 1992; Watson et al. 1994). Although particulate matter problem is a global issue, its concentration is substantially high in developing regions because of the increased levels of dust due to transportation, construction, and other industrial activities (Yang et al. 2001).

Particulate matter can be classified based on their mode of formation into primary and secondary aerosols (Poulakis et al. 2015). Primary aerosols are emitted directly from their sources into the atmosphere, while secondary aerosols are defined as the aerosols that are caused by further reactions such as the oxidation of several gaseous compounds in the air (Zhang et al. 2004). Research on the effects of particulate matters have been gaining remarkable attention due to their meteorological impacts and major health effects as they can penetrate to the respiratory system and the lungs causing direct and permanent health hazards. Plant damage with PM pollution is also observed on the leaves, flowers, and fruits causing an overall lower quality and value which can potentially expose further harm to consumers (Escobedo et al. 2011). Halvorsen and Ruby (1981) estimated that the cost caused by the damage of crops and the diverse effect on the animals and cattle eating those trees or grass to be at billions of dollars in most developing countries. Moreover, particulate matter suspended in the atmosphere reduces visibility by scattering light of wavelengths in the visible range. For instance, the visual range has been reduced by 30% in many parts of the USA due to suspended particulate matter (Jimoda 2012). Moreover, the deposition of particulate matter on building materials and cultural article surfaces can cause damage and soiling, thus reducing the aesthetic appeal and useful life of these structures. Some of the particular concerns of PM effect on material are their impact on the stability of critical civil structures such as bridges, highways, railways, hospitals, and schools leading to catastrophic failures, accidents, and loss of life in addition to billions of maintenance or repair cost (National Research Council 1979).

In this review, we discuss the findings on two main types of particulate matter based on particle diameter (PM_{10} and $PM_{2.5}$), their sources, and deposition on surfaces. In the following sections, we consider mainly the effect of particulate matter deposition on surfaces and materials since the effects of PM on health, agriculture, and natural ecosystems have been well studied and reported elsewhere (World Health Organization 2003; Arslan and Aybek 2012; Jacobson 2008). A special section of this review will focus on the economic impact of PM on solar power production specifically, as well as presenting few sustainable mitigation strategies to control particulate matter pollution.

Methodology of literature review

Grant and Booth 2009 have analyzed 14 types of reviews that are common in research. The 14 review types are rapid review, scoping review, state of the art review, systematic review, systematic search and review, systematized review, umbrella review, critical review, narrative literature review, mapping review, meta-analysis, mixed studied review, overview, and qualitative systematic review. Each type of the reviews was analyzed against a simple analytical framework that includes the Search method, Appraisal, Synthesis, and Analysis of its results (SALSA). Among the mentioned review types, narrative literature review has the scope of describing published materials in order to provide an examination of recent or current literature covering wide range of works in the topic at various levels of completeness and comprehensiveness. It is of critical importance for broad spectrum of readers, giving an in-depth value for new researchers in the field. The perceived strengths of this type of review are that it identifies what has been accomplished previously, allowing for consolidation and paves the road for building on the previous works to avoid duplication and to fill possible knowledge gaps in a specific research domain.

We used searching engines such as Google, Google Scholar, Scopus, and ScienceDirect databases for literature review sources. The keywords that we used are *atmospheric aerosols*, *airborne particulate matter*, *effect on materials*, *solar*, *climate*, *mitigation*, *soiling*, *radiative forcing*, *economy*, *acid rain*, and *dust*. The investigation included all sources from 1900 to July 2018. Our search criteria imposed no language restrictions. The initial screening included titles, abstracts, and all types of research in the form of research articles, review articles, books and book chapters, thesis, and reports. The search engines resulted in 338 sources with Fig. 1 and Table S1 showing the study selection flowchart as per our review. The excluded references were not directly relevant to our review and mainly focused on the health impact of particulate matter, modeling, and simulation of PM for the sake of comparison between various models and conditions, investigation of anthropogenic PM due to specific emissions from mining, stone crushing, coal burning, volcanic eruptions, indoor PM characteristics, etc.

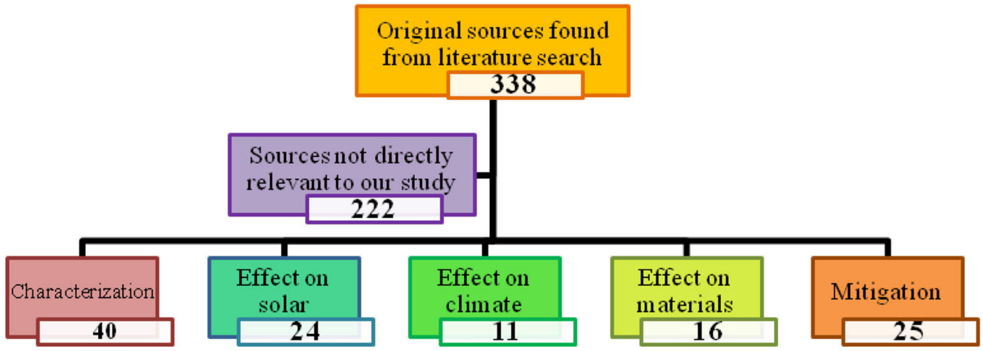

Fig. 1 Study selection flow chart. The initial selection started with 338 documents and the final selection was based on the direct relevance to our review based on the below five categories

Literature review

Particulate matter composition

Several methods can be used for the physical and chemical characterization of PM. Most sampling and chemical analysis methods of particulate matter depend on the sample type and parameters to be measured. These involve the collection of the particles, storage, transport, and preparation before chemical analysis procedures (Pöschl 2005; Finlayson-Pitts and Pitts 2000).

Aerosols are usually composed of particulate and gas-phase components with the carbonaceous components accounting for a large fraction of air particulate matter (Pöschl 2005). These components mainly affect the physiochemical, biological, climate, and health-related properties of particulate matter (Pöschl 2005). The total carbon (TC) content in PM is defined as the sum of all carbon contained in the particles and is divided into two parts: the organic carbon (OC) and the black carbon (BC) or the elemental carbon (EC). Black/elemental carbon is usually determined by optical and thermo-chemical oxidation techniques, while the organic carbon is determined by the difference between total carbon and black carbon or elemental carbon (Gelencser 2004; Pöschl 2005). The organic components of particulate matter can further react with the atmospheric photo-oxidants (OH, O_3, NO_3, NO_2, etc.), acids (HNO_3, H_2SO_4, etc.), water, and UV radiation to form secondary pollutants.

Particulate matter sources and deposition

Particulate matter can be also classified based on their particle size into coarse, fine, and ultrafine particles (Table 1). Coarse particles have particle sizes between 2.5 and 10 μm. Fine particles have sizes of 2.5 to 0.1 μm, while ultrafine particles have sizes less than 0.1 μm.

Particulate matter has different shapes and morphology as well as can be seen in Fig. 2. Particulates can be solid spheres, hollow spheres, flake, irregular shaped, and aggregate. Moreover, the coarse and fine particulate matters vary in their sources, physical properties, formation processes, and their chemical composition. Hence, they have different effect and impact on other systems such as human health, environment, air quality, structures, and surfaces (Wiman 1985).

In addition, particulate matter can be classified based on their state in the air as primary and secondary. Primary particles are formed directly from their sources due to human and natural activities, while secondary particles are formed from air contaminants that further react to form PM.

There are two main sources of airborne particulate matter: natural or anthropogenic sources (Fuzzi et al. 2015). Ginoux et al. (2012) reported that 75% of the global dust emissions are of natural origin, while 25% are related to anthropogenic emissions. These ratios vary considerably from one place to another on Earth. In a recent review, Karagulian et al. (2015) calculated the regional average sources of PM by investigating 419 source apportionment records from studies conducted in 51 countries around the world. They concluded that 25% of urban ambient air pollution from $PM_{2.5}$ is contributed by traffic, 15% by industrial activities, 20% by domestic fuel burning, 22% from unspecified sources of human origin, and 18% from natural dust (such as desert dust) and salt as depicted in Fig. 3.

Moreover, it was found that humidity increases the impact of PM on structure and material surfaces, regardless of their mode of formation (primary or secondary aerosols; Fuzzi et al. 2015; Cleaver and Tyrrell 2004; Lambert and Valsamis 2013). It was also reported that aerosols emitted from marine environment make up one of the largest components of particulate matter such as mineral dust, volcanic ash, and biological aerosols in the Earth's atmosphere, while on the other hand, mineral dust is often a dominant component of atmospheric aerosol in large regions of the planet (Fuzzi et al. 2015).

In addition to the global view on PM speciation mentioned above, several researchers have reported on the characteristics and sources of PM in different parts around the world. In *Asia*, Azarov et al. (2015) studied the seasonal variation in the air content of dust particles ($PM_{2.5}$ and PM_{10}) depending on the intensity of transport traffic in one of the resort cities in the Caucasus Mineral Waters region in Russia. The researchers developed distribution functions of concentration maximums. The coefficient values of the specified functions were found

Table 1 Characteristics of coarse, fine, and ultrafine particles, adopted with modification from United States Environmental Protection Agency (2009)

	Coarse particles ($PM_{10–2.5\ \mu m}$)	Fine particles ($PM_{2.5–0.1\ \mu m}$)	Ultrafine particles ($PM_{<0.1\ \mu m}$)
Mode	Coarse	Accumulation	Nucleation
Formation and sources	Break-up of solids and droplets Erosion of land Suspension of dust Resuspension of road debris (tire/brake wear) Ocean spray Ash (black smoke) from uncontrolled combustion Construction and demolition Disturbance of surfaces (agriculture, mining, quarrying, unpaved roads) Biogenic emissions (pollen, fungal spores)	Condensation of atmospheric gases Coagulation of ultrafine particles Reactions of component gases of particles Evaporation of water droplets containing dissolved gases Combustion of fossil and biomass fuels Industrial processes (smelters, refineries, steel mills, mining)	Nucleation and condensation of atmospheric gases High temperature combustion (including vehicle exhausts)
Composition	Organic and elemental carbon Sulfates Nitrates Chlorides Oxides of crustal elements Sea salt Plant and animal debris Bacteria	Organic and elemental carbon Sulfates Nitrates Ammonium Metals Organic compounds Water Bacteria Viruses	Organic and elemental carbon Sulfates Metals Organic compounds
Physical characteristics	Large mass	Large surface area	High particle number
Spatial/temporal variability	High	Low	Very high
Atmospheric lifetime	Minutes to days	Days to weeks	Minutes to hours
Distance traveled	Usually < 1–10 km	100–1000 km	Usually < 1 to 10s of km (100s to 1000s of km in dust storms for the small size tail)
Removal process	Gravitational deposition Scavenging by rain	Gravitational deposition Formation of cloud droplets and rain out	Coagulation, adsorption, condensation, diffusion to rain droplets
Extent of physiological deposition	Upper airways (primary bronchi)	Lower airways (terminal bronchioles and alveoli)	Extrapulmonary organs

for dust pollution in general and for fine particulate particles with and without vehicle traffic as well as in the residential and industrial zones based on the field investigations. Another study was conducted by Police et al. (2016) on the chemical characterization and source apportionment of PM in an industrial coastal city in India. The elemental composition showed that aluminum was dominant in several locations within the area, followed by potassium and calcium. The source apportionment was conducted via Positive Matrix Factorization developed by USEPA which identified six and seven sources in two main locations. Five of these sources were common in both sites, namely, crustal matter, sea salt spray, coal combustion, fuel oil combustion, and metal industry. Afzali et al. (2014) investigated the influence of meteorological parameters on predicting ambient PM_{10} concentrations based on data sampled from 2008 to 2010 in an industrial area in Malaysia. They found a weak relationship between ground level PM_{10} concentration and the meteorological parameters in that area using statistical models. In Mongolia, Davy et al. (2011) investigated the composition and sources of particulate matter pollution in the capital city (Ulaanbaatar). It was found that there were high PM pollution episodes during winter and during dust storm events in the spring and summer. The composition of PM samples indicated the presence of black carbon as well as several elements such as Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Mn, Fe, Cu, and Zn. The receptor modeling (Positive Matrix Factorization and mass-back trajectories) using PM data collected from 2004 to 2008 indicated that crustal matter sources were the primary contributors to the coarse particle fraction, while combustion sources (mainly coal combustion, biomass burning, and motor vehicles) dominated the fine fraction. In another study conducted to assess the long-term trend of fine PM at two urban sites in Lahore/Pakistan during 2007–2011, Khanum et al. (2017) found that there was a long-range transport of $PM_{2.5}$ from India to Pakistan during February to October whereas long-range transport was observed from Pakistan to India during November to January. Those results were considered critical to assess the effectiveness of pollution

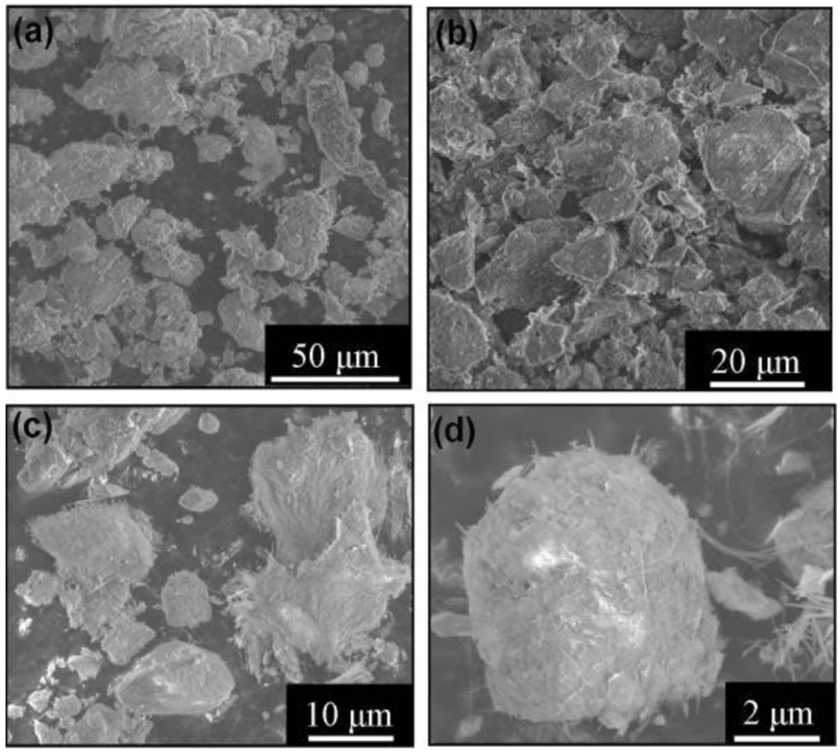

Fig. 2 Representative SEM micrographs (**a**–**d**) of desert dust particles collected directly from PV panels (Aissa et al. 2016)

control strategies in Lahore and other similar cities in the area. In Seoul in Korea, Kim et al. (2017) recently presented the results of a detailed source apportionment study of the high particulate event that took place in February 2014. The critical characteristics of the high PM events in the area revealed the presence of complex chemical transformation from different sources. For instance, the high ammonium sulfate and ammonium nitrate concentrations in PM in Seoul Metropolitan Area resulted from Chinese SO_2 and NO_x as well as South Korean NH_3 emissions. This finding has highlighted the importance of fine-scale source apportionment with a careful view of region-by-region contributions.

In *North America*, in a study conducted in Virginia, USA, the researcher collected PM samples at urban and rural

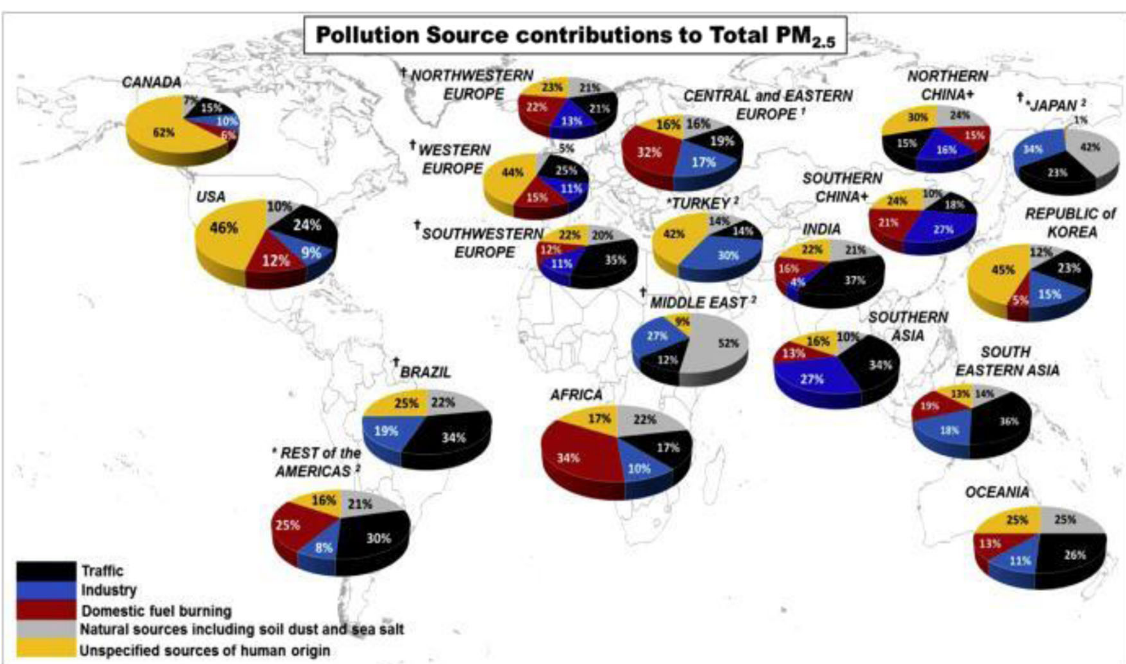

Fig. 3 The average population-weighted sources of total $PM_{2.5}$ in urban sites (Karagulian et al. 2015)

locations (Jeng 2010). The ambient PM samples were characterized for their physical characteristics and chemical composition. The background samples which were collected at the rural areas showed lower concentrations of organic carbon, elemental carbon, and polycyclic aromatic hydrocarbons (PAHs) compared with the samples collected at urban areas. These results also showed that urban PM samples had higher redox activity correlated with PAHs and other organic compounds in their composition mainly due to high traffic flow. Recently, Dickerson et al. (2017) have investigated the concentration of fine particulate matter at 379 urban sites in the USA over the years between 2000 and 2014 with the aim at comparing the average concentration of $PM_{2.5}$ around July 4th due to firework-related chemicals. The authors found sharp and statistically significant increase in barium, chlorine, copper, magnesium, potassium, and strontium compared with other normal days. Another study conducted by Clements et al. (2014) on the chemical characterization of coarse particulate matter in the Desert Southwest of Arizona in the USA found that coarse particle concentration was highest in the spring and fall which was consistent with harvesting seasons. The composition of coarse particles was dominated by crustal material representing about 50% of the mass on average, while organic matter represented 15%. On the other hand, fine particles contained 30% of crustal material with domination of organic matter of about 37%. In another study conducted by Meng et al. (2018) to estimate $PM_{2.5}$ speciation concentration over Southern California, the developed model that used 4.4 km resolution aerosol data was able to explain 66, 62, 55, and 58% of the daily variability in $PM_{2.5}$ sulfate, nitrate, organic carbon, and elemental carbon concentrations during the period between 2001 and 2015. Squizzato et al. (2018) investigated the spatial variability, temporal trends, and economic influences of $PM_{2.5}$ and gaseous pollutants in New York state during 2005–2016. This interesting study indicated the importance of mitigation strategies as well as changes in the federal and state agencies policies to improve air quality. The financial/economic crisis that faced the USA between 2007 and 2009 as well as the changes in coal and natural gas prices drove a shift in the fuels used for electricity generation. Hence, by 2016, $PM_{2.5}$ levels decreased significantly at all sites in the state (9 suburban, 9 rural, and 13 urban). Similarly, SO_2 concentrations decreased significantly at all locations with the highest slopes observed at the urban sites. Moreover, a significant relation was found between $PM_{2.5}$, primary pollutants, and economic indicators. An overall conclusion indicated that the decrease in electricity generation by coal led to the decrease in $PM_{2.5}$ and other gaseous pollutant concentrations. This study is of paramount importance for policy and decision makers indicating that energy sector was a major driver for the reduction in $PM_{2.5}$ concentration in New York state.

In *New Zealand*, Davy et al. (2012) studied the composition and source contribution of air particulate matter pollution in a suburban town located at the southern end of the North Island in New Zealand from July 2006 to September 2008. The results of the sources (using receptor modeling) showed that coarse particles were mainly due to marine aerosol and crustal matter, while fine particles were dominated by biomass burning, secondary sulfate particles, as well as marine aerosols. Arsenic presence in fine particles was highlighted suggesting the use of copper chrome arsenate-treated timber used for domestic heating. Moreover, the seasonal variation in PM concentration showed that biomass burning was largely responsible for high fine particle pollution in the winter while marine aerosol featured significant PM_{10} concentrations all year due to New Zealand location near to the ocean.

In *Africa*, Ofosu et al. (2012) investigated the characteristics and sources of fine particulate matter in a semi-urban town in Ghana. PM collected on quartz fiber filters and nucleopores were analyzed for their elemental and carbonaceous compounds. Eight sources were identified with close values of the main four sources (fresh sea salt, diesel emissions, gasoline emissions, and soil dust) using Positive Matrix Factorization method.

Several studied were conducted in *Europe*. Rogula-Kozlowska (2016) has conducted a study on the composition of size-segregated urban particulate matter in Southern Poland. The aerodynamic diameters of the particles were found to be in the interval of 0.03–40 μm with domination of various organic and inorganic compounds in their composition for the smallest particle fraction ($PM_{0.03–0.26}$). In another study on the chemical composition and sources of fine particulate matter in Krakow, Poland conducted by Samek et al. (2017), it was found that there were several main contributors to PM fine pollution in the city due to steel industry (Fe and Mn), traffic and road dust (Cu, Zn, Pb, V, and Ni), construction dust (Ca and Ti), biomass and coal combustion (Cl and K), as well as non-ferrous metallurgical industry (Co, As, Cr, and Ba). Moreover, Sarti et al. (2015) investigated the metal composition of fine particulate (PM_1 and $PM_{2.5}$) collected in the vicinity of a suburban-farming area northeast of Bologna in Italy. The results showed that Fe, Al, and Zn were the most abundant elements representing 80% of the total amount analyzed. Although a municipal incinerator is located at the site of research, there was no noticeable difference in the concentration of metals between the incinerator samples and the control site samples.

In this context, it is worth mentioning that very few studies are available on the characterization and source apportionment of particulate matter in the Arabian Gulf countries located in the Middle East area. Khodeir et al. (2012) reported on the sources and the elemental composition of $PM_{2.5}$ and PM_{10} in Jeddah, a coastal city in the Kingdom of Saudi Arabia. The study presented the first comprehensive investigation of PM and their sources in the country. The $PM_{2.5}/PM_{10}$ ratio was about 0.33. The chemical composition was modeled to find the sources of these particulates. Five source categories were contributing significantly to $PM_{2.5}$, while five sources were attributed to PM_{10}. The common sources of $PM_{2.5}$ and PM_{10} were heavy oil combustion characterized by high Ni and V, resuspended soil characterized by Ca, Fe, Al, and Si, and a mixed industrial source. On the other hand, two distinguished sources were assigned for $PM_{2.5}$, namely, traffic as identified by high levels of Pb, Br, and Se and another industrial source mixture, while marine aerosol source was assigned for PM_{10}. A following study by Alharbi et al. (2015) reported on the characteristics of PM in the capital city of Saudi Arabia without investigating the sources of these particulates. The results showed that PM_{10} concentration during September 2011–September 2012 was approximately three times higher than the country's ambient air quality standards. Moreover, metals and ions contributed to about 21.5 and 16.2% of the PM concentrations, respectively. When seasonal variation was investigated, it was found that summer had 84% higher PM concentration compared to the winter, primarily due to frequent dust storms. The crustal matter species in the content of PM was mainly composed of Fe, Ti, Ca, and Mg. The weekdays PM concentrations were 17% more than weekends indicating human activities that contribute to the elevated PM levels.

Effect of particulate matter on materials

Soiling on surfaces and PV modules

Power output from photovoltaic module is dependent on several factors that include temperature, installation location, tilt angle, and soiling (Rao et al. 2014, b; Sulaiman et al. 2014). Soiling is defined as the degradation mechanism that can be caused by the deposition of dust on material surfaces (Isaifan et al. 2017; Martinez-plaza et al. 2015; Isaifan et al. 2018, b). Settlement of dust on photovoltaic (PV) surfaces might be uniform and non-uniform depending on weather conditions, PV size, location, and inclination. Small PV arrays may have uniform dust accumulation compared with large ones. In addition, wind and rainfall often encourage soiling on PV surfaces. This process can be remedied by cleaning, washing, or repainting, depending on various other conditions of the soiled surface (Bhattacharjee et al. 1999). Soiling also impacts the optical properties by reducing the reflectance that results from the deposition of airborne PM on the external surfaces of buildings or other structures (Jimoda 2012). Soiling effect on man-made surfaces can severely deteriorate the artwork, historical heritage value, efficiency, and durability of materials and structures. Particulate matter tends to soil cities by covering building, streets, pavements, floors, bridges, and other critical civil structures, which require sweeping or dusting more frequently, thus further increases the cost of maintenance and public health burden. In addition, due to the alkaline nature of dust, painted surfaces such as walls, doors, and automobiles can also be easily damaged. Beloin and Haynie (1975) investigated the effect of soiling on the paints of exterior walls. They found out that soiling was directly proportional to the square root of the suspended particle dose in the case of white paint. The degree of damage on surfaces is dependent on the chemical and optical properties of PM. Newby et al. (1991) reported that PM emissions from diesel-driven vehicles have much higher degree of soiling due to the higher content of elemental carbon, which is more likely to adhere to surfaces compared with petrol or domestic coal emissions (Penner et al. 1993). As indicated before, compounding of natural dust emissions such as diesel and humidity can make the situation more alarming, reducing the reliability of structures in shorter period of time, and also making the cleaning or other anti-dusting techniques more difficult and more costly compared with natural dust only.

Another significant effect of soiling is related to the reduction of photovoltaic cell efficiency, which is an emerging problem with an increase of investments in solar PV installations in countries in the Middle East region such as the such as the countries of the Gulf Cooperation Council (GCC), which includes Qatar, Saudi Arabia, Kuwait, the United Arab Emirates, Bahrain, and Oman. In a recent review on the soiling effect on solar panels, Maghami et al. (2016) summarized several factors that reduce the solar power output such as:

1. Sun tracking losses
2. Mismatch losses
3. Shading losses
4. Diode and connection loss
5. Soiling losses

Moreover, the authors reported that there are three main reasons that cause dust accumulation as shown in Fig. S1 (Maghami et al. 2016). Dust accumulation on PV surfaces decreases their photocurrent output since it mainly affects the optical properties of the PV modules (Fig. 4). Several studies have reported on the direct effect of soiling on the optical properties of photovoltaic glass in different areas in the world with emphasis on quantifying soiling effect by measuring the corresponding optical losses (Yilbas et al. 2015; Beattie et al. 2012; Neff et al. 2008). Salim et al. (1988) reported that 32% reduction in the PV module efficiency have been observed after 8 months of solar cell exposure dust. Sayigh et al. (1985) have revealed a power loss of about 11.5% after only 72 h of dust exposure. In addition, soiling on PV leads to an increase of the per kilowatt energy production cost due to frequent and unpredictable cleaning needs.

Experimentally, El-Shobokshy and Hussein (1993) have been investigating the effect of accumulation of dust and particulate matter onto the surface of photovoltaic cells under well-controlled solar simulator light source. He used five

Fig. 4 Soiling of solar panels at the Solar Test Facility in Doha (The State of Qatar) after dust storm in 2014 (Aissa et al. 2016)

kinds of dust (three limestone samples, cement, and carbon particulate) with different physical properties. They showed that fine particulate matter has significant effect on the performance of photovoltaic cells which directly decrease the performance of photovoltaic cells and causes higher loss in power output (El-Shobokshy and Hussein (1993). Moreover, El-Nashar (2009) evaluated the seasonal effect of dust on solar desalination plant in Abu Dhabi/the United Arab Emirates where they found that transmission loss of the glass covers was higher during summer seasons. That was due to the greater accumulation of dust on solar panel surfaces as a result of sand storms and lack of precipitation during the months of summer in that region (El-Nashar 2009). More specifically, under very dusty conditions, the transmittance decreased from an initial value of 0.98 (on clean glass) to a low value of 0.6 (over the soiled glass) causing production drop from 100 to 40% relative to the clean collector production level. Therefore, a weekly cleaning schedule is required to maximize PV power production under dusty conditions.

In another study, El-Nashar (2009) reported on an economic analysis of the dust effect on PV modules deployed in a temperate climate region, Perth, Western Australia by investigating the performance of three PV modules. Those modules [(a-Si), polycrystalline silicon (pc-Si), and monocrystalline silicon (mc-Si)] were chosen randomly and are representative of represent the solar technologies deployed in Perth (El-Nashar 2009).

In a very recent study conducted by Styszko et al. (2018) on the analysis of dust deposited on solar photovoltaic surfaces in Krakow, Poland which is considered one of the highly polluted cities in Europe in terms of high PM concentrations (Styszko et al. 2018), the researchers studied the time-dependent particle deposition on several identical PV modules during variable exposure periods that ranged from 1 day up to a week. Their aim was to investigate the natural dust accumulation process as affected by different ambient conditions such as wind velocity, direction and magnitude, humidity, and rain amount. The data obtained by such studies in different locations around the world can be useful for the prediction of dust deposition under different environmental conditions which is of interest to system developers and operators (Aissa et al. 2016; Styszko et al. 2018). The same research group continued this work by another investigation to study the effect of the natural deposited dust on the PV module efficiency (Jaszczur et al. 2018). They found that after 1 week without rain, 300 mg/m^2 of dust deposition rate was obtained causing PV efficiency loss of 2.1%. Moreover, the losses in efficiency were not only mass dependent but also correlated with the properties of dust. The authors as well used the experimental results to develop a simple mathematical model for the performance degradation of PV caused by dust mass deposited on the front cover surface of the PV modules.

Paudyal et al. (2017) conducted experimental work to study the transmittance losses of solar PV caused by soiling in Katmandu, Nepal. The results showed an alarming reduction in transmittance as high as 69% over a dry dusty period of no rain events. Accordingly, the power output of the dusty solar module decreased by 29.8% compared with a module that was cleaned on daily basis.

Kazem et al. (2014) reviewed dust effect on PV utilization in Iraq. The work started by an overall look at the Iraqi geographical and metrical characteristics in addition to the human activities that increased desertification in Iraq. Those activities have reflected on the increasing sand and dust storms in the country. The review as well has shed light on PV system performance as highly affected by dust and sand storms influencing the energy collected. It also provided recommendations to better utilize PV in order to meet the increasing demand on electricity which is considered now an obstacle to Iraq's development due to the lack of reliability on electricity supply.

Figgis et al. (2017) reviewed recent PV soiling particle mechanics in desert environments. The summary shows that soiling mechanisms are largely controlled by air flow which can impact rapid deployment of PV in desert regions. Atmospheric air flow is usually turbulent which affects the inertial deposition of particles on PV surfaces. Another factor that plays role in PV soiling is the particle size distribution, since deposition velocity is dependent on size with large particles dominating soiling mass. Another parameter is the tilt angle or the surface orientation of PV module where several studies concluded that PV power loss is greatest for horizontal surfaces and lowest for vertical ones. Moreover, resuspension of dust particles is highly sensitive to wind speed as the particle detachment from the surface is related to the square of flow velocity. Resuspension is also strongly dependent on particle size with larger particles tending to blow off PV modules while smaller particles remain immune to removal by wind.

The economic burden to clean, paint, and repair surfaces as a result of particulate matter deposition has been presented and discussed before (McCarthy et al. 1984; Tidblad et al. 2010). Rabl et al. (1998) estimated the damages caused by soiling of buildings as the sum of the repair cost and amenity cost. The amenity loss is equal to the cleaning cost for a zero-discount rate. Therefore, the total damage cost is twice the cleaning cost. For the specific case of damage cost caused by PM_{10}, Watkiss et al. (2001) used Rabl estimation to calculate PM_{10} damage cost for the years 2008 and 2010 to be 336.6 million/year and 176.7 million/year, respectively. McCarthy et al. (1984) developed two damage cost models to quantify the effects of ambient air pollutants on man-made materials exposed in urban environment. The first model called "prevailing practice model" is based on a critical damage level, which is defined as the amount of damage that is usually accepted before remedial action is taken, and is assumed to be constant. The change in maintenance schedule will be, then, calculated from the change in the rate of damage, which is a function of pollutant concentration (McCarthy et al. 1984). In the second model, which is called "the least cost model," the critical damage levels and maintenance criteria are directly specified by the user. The model, then, calculates the cost of system's use life for maintenance schedule based on the pollution levels. It is a well-known fact that uncertainty in maintenance needs will significantly increase the cost of maintenance and operations when compared to scheduled, hence predictable, maintenance conditions (Yan et al. 2004).

The economic analysis to investigate the economic losses caused by deposition of dust on a PV system takes into consideration cleaning procedure and schedule preformed effectively (Koç et al. 2004). According to the suggested model by El-Nashar (2009), the cost of PV production losses (CPL) depends on energy losses, saving value (RS), and incentive value (RINC).

$$CPL = energy\ losses\ (RS + RINC) \tag{1}$$

$$Energy\ losses = (P_{max}\ output\ in\ clean\ condition - P_{max}\ output\ in\ dusty\ condition) \times peak\ sun\ hours\ over\ \text{a}\ certain\ time\ period \tag{2}$$

In this case, it is recommended that the maintenance activity cost (CMA) would be the summation of the cost of materials (Cm) applied for cleaning and the cost of workforce (Cwf). Therefore, cleaning process should be performed when the losses caused by dust (CPL) are greater than the maintenance cost (CMA).

Radiative forcing, climate change, and visibility

Radiative or climate forcing is defined as the difference of insulation (sunlight) absorbed by the Earth and energy radiated back to space (Shindell 2013). PM can influence the climate change via two ways. PM can directly scatter and absorb solar irradiation or indirectly favor the formation of cloud condensation nuclei (Jimoda 2012). Hence, direct radiative forcing by scattering of light due to aerosol particles or through absorption of light due to aerosol particles occurs when the particles with diameters similar to the wavelength of the incident light produce negative forcing (cooling effect). On the other hand, absorption of light by particulate matter involves the conversion of incident light into thermal energy, thus producing positive forcing (warming effect). Nevertheless, in the case of indirect radiative forcing, the change in PM concentration or composition induces changes in the microphysics, radiative properties, and lifetime of clouds because aerosol particles serve as cloud condensation nuclei (CCN) (Jimoda 2012; Haywood and Boucher 2000). It is reported that for certain amount of liquid water content, an increase in the CCN number due to pollution leads to an increased amount of smaller droplets, which results in a net cooling effect (Fig. S2) (Pöschl 2005).

Tainio et al. (2013) estimated the population exposure to $PM_{2.5}$ in Poland for three decades: the 1990s, 2040s, and 2090s in connection with climate change models. They found that climate change might have reduced the levels of exposure to anthropogenic PM pollution in the future by 6% in Poland. The decrease in $PM_{2.5}$ concentration is assumed to be as a result of the increase in winter precipitation in that area as per climate model simulations for the periods 1990s and 2040s, while this reduction was not supported for the 2090s. Such results are considered with critical importance for further cost-effective preventative actions planning in Poland.

Moreover, Bergin et al. (2017) used the Global Climate Modeling tool to estimate both direct and diffuse irradiances based on particulate matter and clouds to account for their effects on the visible flux that reaches surfaces on Earth. This model also estimates dry deposition fluxes of species which is dedicated to evaluate the impact of deposited PM on the transmission of solar energy of PVs. In their work, they included the direct effects only due to the large uncertainties in the indirect effects. Figure S3 shows the model results for different areas in the world (Bergin et al. 2017).

Zhuang et al. (2014) studied the optical properties and radiative forcing of urban aerosols in Nanjing in China through the interpretation of PM measurements in a two-phase study (phase 1: January 18 to April 21, 2011; phase 2: April 22, 2011 to April 21, 2012). The first phase coincides with Spring and Lantern Festivals and is characterized with high $PM_{2.5}$ pollution that reaches up to 440 μg/m^3, possibly due to significant discharge of fireworks. The annual single scattering albedo (a measure of the diffuse reflection of solar radiation that cast back into the atmosphere) of aerosols ranged from 0.9 to 0.92. Aerosol direct radiative forcing (DRF) was found to be sensitive to surface albedo. Over bright surfaces, solar radiation was more absorbed by absorbing aerosols and less scattered by scattering aerosols. Moreover, it was found that the albedo in summer was larger than in other seasons. Hence, both total and absorbing aerosol direct radiative forcings showed seasonal variation with stronger DRF in summer of about 17.9 W/m^2 at the surface while in winter; it was about 14.7 W/m^2.

Moreover, Xu and Lamarque (2018) have reported recently on the impact of climate change caused by greenhouse gas emission on $PM_{2.5}$ levels. The researchers used a Community Earth System Model 1 to show that the global surface concentration and black and primary organic carbon would still increase by 5–10% at the end of the twenty-first century (2090–2100) even if the anthropogenic emissions would remain at the same level as of the year 2005. More importantly, the decrease in wet removal flux of $PM_{2.5}$, despite an increase in global precipitation, will be a primary cause to the increase of $PM_{2.5}$ levels. These simulation results can be of critical importance to mitigate for future climate change impacts to be accounted for to define the future emission standards necessary to meet air quality standards.

One of the few studies that investigated the impact of particulate pollution on visibility was reported by Zhao et al. (2013). In their work, visibility data at Shenyang in China was collected from 2010 to 2012 and the data was correlated with PM mass concentration as well as meteorological parameters and analyzed statistically. The results showed that higher average visibility values were reported in March and September with 19 and 17 km, respectively, while the lowest has occurred in January at approximately 11 km. Among the meteorological parameters considered, wind speed was found to be the main factor that influenced visibility. Moreover, the existence of fine particulate matter has led to significant deterioration in visibility. The diurnal and weekend variations indicated that high PM levels were mainly due to human activity.

PM effect on cultural heritage

The damage caused by particulate matter on heritage and cultural buildings is real and in many cases measurable (Watt et al. 2009). Particulate matter air pollution has affected different types of monuments that were built from different materials over the last centuries. Watt et al. (2009) edited a book where they gathered several studies and research works that looked into this topic and mostly focused on two types of damages: corrosion and soiling. They started by looking at the pollutants levels in the past, currently, and as projected. This step is of paramount importance as the pollutant levels after the policy pioneered by the Clean Air Act to reduce coal burning have dramatically changed.

In heritage environment, indoor activities such as cleaning or physical activities can further cause variations in PM concentration. Nevertheless, the main sources actually come from outside such as through the windows, doors, and any openings or gaps. For example, in a study in California Museum, the use of windows for ventilation in addition to the lack in air filtration inside the museum showed and indoor/outdoor PM ratio of 1 (Ligocki et al. 1993). The penetrating fine particles from outdoor to indoor environment will tend to move around via Brownian motion and deposit on cracked walls and other surfaces. The deposition rate of these particles greatly depends on the air flow as well as on the particle size which is driven by gravity. On the other hand, indoor emissions were found significant in some specific heritage locations such as in churches where candles are burned (Grau-Bove and Strlic, 2013).

Grau-Bove and Strlic (2013) claimed in their recent review that not much has been considered with regard to the effect of fine particulate matter on heritage buildings. The aesthetic and chemical harm that fine particulate matter might impose on buildings is not reflected in the current state of the art research. Moreover, their work has served a double purpose. First, they showed the relevant risk of fine particles to cultural heritage indoors, and secondly, they provided a sort of guidance to heritage managers on the distinct behavior of fine particles in heritage environment. Moreover, the authors paid attention on particles derived from combustion sources for their specific composition, activity, and hence their effect. The studies showed that these particles have different morphologies and their composition varies depending on their sources: diesel, coal, tobacco, burning of candles, etc. Diesel particulates are mainly composed of elemental carbon with other metallic traces (Ca, Fe, Mg, Zn, Ni, Ba, and Pb). The total carbon in these particles varies based on the fuel type, engine load, and engine type, but it can take the range between 75 and 90%. In addition, candle burning indoor can emit ultrafine particulate matter whose composition is dominated by phosphates or alkali nitrates which comes from additives.

The major corrosion factor was sulfur dioxide while black smoke has caused the building colors to darken. Nevertheless, the way each pollutant affects heritage buildings have been presented across the world. In those studies, assessment of corrosion and soiling rate enables the scientists to develop equations to predict the amount of damage each pollutant would cause based on its concentration. These equations are called "dose–response functions." These studies are expensive and take long time to be conducted; therefore, these functions are available for specific materials.

The other specific effect of PM on heritage structures as depicted earlier is due to soiling. Soiling is directly proportional to the loss of reflectance and lightness. One of the first dose–response functions was developed by Belion and Haynie in 1975 with the assumption that soiling is proportional to the square root of PM concentration (Ligocki et al. 1993). The soiling indoor is associated with black stains and potential degradation of monument structures. In addition, aged diesel PM is hygroscopic which favors water adsorption and hence accelerates the oxidation of materials. Damaged layers have been also detected on indoor murals and wall paintings. On the other hand, structures of zinc and steel have been corroded in the presence of deposited particles which increase the overall corrosion rate.

Another impact of particulate matter on the heritage building is their weathering effect of glass which is similar to corrosion of glass in aqueous media. The weathering effect due to the attack of airborne particulate matter can cause degradation of glass surfaces which attracted attention in the second half of the twentieth century when severe degradation of medieval glass windows in European churches and cathedrals was observed. There is very few works on this topic due to the complexity of the multiphase system represented by bulk glass/glass surface/water film. Nevertheless, it is worth mentioning that the glass that was produced for those heritage buildings in the medieval periods was mainly composed of potassium and calcium with less concentrations of silica. This composition is much more susceptible to corrosion (Fig. 5), weathering, and particulate attack than modern glass which are mainly soda-lime type (Bunnik et al. 2010; Melcher et al. 2008).

Moreover, typical examples of weathered glass surfaces can be shown in Fig. 6. It can be seen that weathering products such as syngenite and gypsum can be found covering major parts of the glass surface. These weathering products being mainly composed of K and Ca compounds as well as chlorides (NaCl and KCl) are significant constituents of particulate matter (Aissa et al. 2016). Although for the naked eye, the glass surfaces might appear intact, while on a few specimens, depth, cracks, and loose glass blocks can be found (Fig. 6). These compounds appear in different morphologies, and as their amount increases on glass surfaces, more particulate matter is encouraged to deposit on these surfaces causing sever soiling ratios (Bunnik et al. 2010) (Fig. 7).

Rao et al. (2014, b) have reported that in India alone, $45 billion is spent each year to account for corrosion in infrastructure, industrial machinery, and historical heritage. This is partly due to the elevated levels of PM in most Indian cities. Those PM include soot, dust, fumes, residues of fabrics, and buildings. The rate of damage of the exposed surfaces is further accelerated with wind, presence of sulfur dioxide, and moisture.

Acid deposition on materials

Acidic deposition refers to both wet and dry depositions, with wet acidic deposition being commonly referred to as acid rain (Stern et al. 1984). Acidic rain water has low pH due to the presence of sulfuric acid (H_2SO_4), nitric acid (HNO_3), and carbonic acid (H_2CO_3) dissolved in the rain or formed in the droplets. Dry deposition takes place when particulate matter, air pollutants such as SO_2, NO_2, and HNO_3, and acidic aerosols get in contact and stick to other surfaces. If the surfaces are moist or contain liquid, the gases penetrate into the solution and the acids formed are similar to those that fall in the form of acid rain.

Fine particulate matter and acid deposition issues are closely linked and have been directly responsible for ecosystem and material damage (Bhattacharjee et al. 1999). Samples collected from eastern USA have shown dominance of large sulfate fraction in the chemical composition in the primary and secondary PM samples (Bhattacharjee et al. 1999). In urban areas, this has greatly affected many construction materials and paints in addition to their effect on range of agricultural and natural ecosystems leading to massive summer fish kills of Chesapeake Bay and Long Island (Bhattacharjee et al. 1999).

Rodriguez-Navarro and Sebastian (1996) conducted the first work that experimentally demonstrated the relationship between motor vehicle emission PM and the decay of stones via sulfation processes (the well-known phenomenon of Black crust formation). In their work, the dynamics of building material decay by particulate matter was explained by their experimental data, which indicated that particulate matter play a critical role in the fixation of atmospheric SO_2 as sulfates (gypsum) on calcareous materials in the presence of humidity. They have also proved experimentally that there is a relationship between PM composition and sulfur dioxide fixation rate. More specifically, they found that diesel engine exhaust, which is primarily composed of soot and metallic particles bearing Fe and Fe-S as major elements and of Cr, Ni, Cu, and Mn as trace elements, plays the largest part in the catalytic oxidation rates of SO_2 while the emissions from gasoline engines had minor quantities of soot and high concentrations of Pb- and Br-bearing particles with a lower rate of SO_2 fixation as gypsum on limestone (Rodriguez-Navarro and Sebastian 1996). To test their hypothesis, the authors placed samples

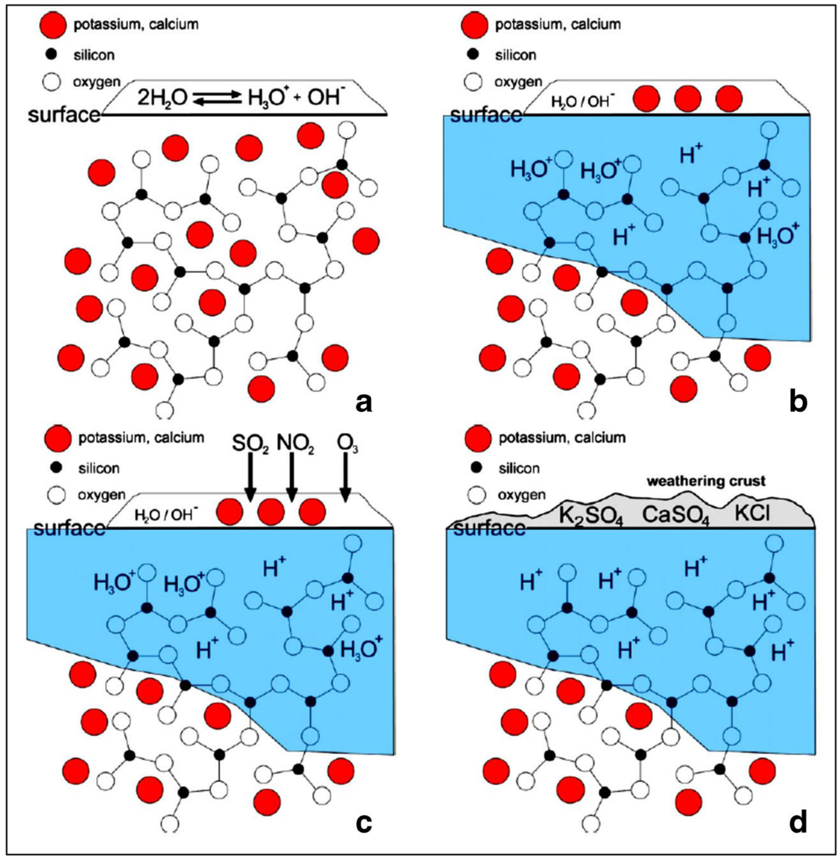

Fig. 5 Scheme of the stages involved in the weathering of glass showing the formation of a water film on the glass surface (**a**), the extraction of cations (**b**), the dissolving of acidifying gases (**c**), and the formation of a weathering crust (**d**) (Bunnik et al. 2010)

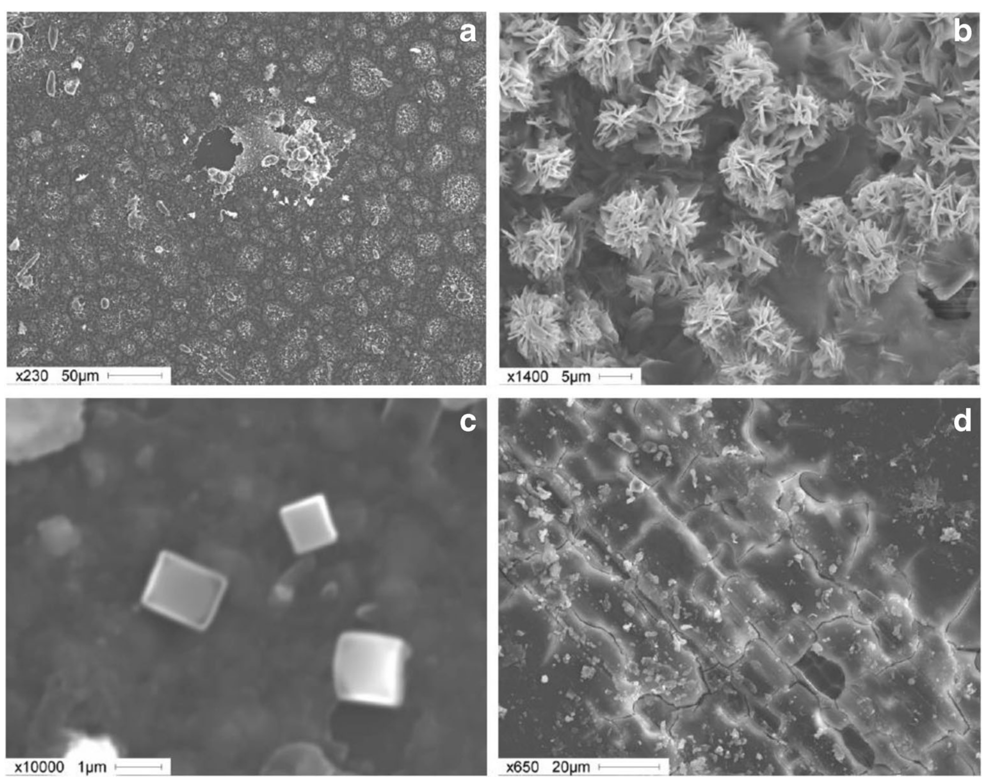

Fig. 6 Weathered glass surfaces after 6 months of field exposure: thick weathering crusts mainly consisting of syngenite (images **a** and **b**), NaCl crystals (edge length approx. 1 µm, **c**), and a cracked and pitted glass surface (**d**) (Bunnik et al. 2010)

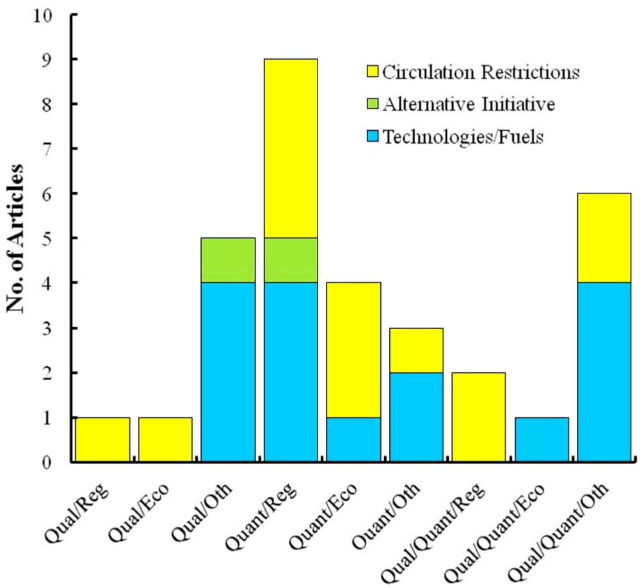

Fig. 7 Air pollution policy management. Qual, qualitative; Quant, quantitative; Reg, regulatory approach; Eco, economic incentives; Oth other, modified from Slovic et al. (2016)

of (fresh) uncovered limestone and limestone samples covered with diesel and gasoline exhaust particles and dust into an SO_2 chamber. The samples were then analyzed with XRD after 48 h from the beginning of the experiment. Small amount of gypsum quantities ($\leq 5\%$ by weight) were found on the limestone slabs covered with gasoline compared with ($\geq 15\%$ by weight) detected in the limestone samples covered with diesel exhaust particulate matter. However, larger quantities of gypsum were found in samples covered with particulate matter (dust) ranging between 15 and 20% by weight. No gypsum was detected on clean limestone. Moreover, limestone samples collected from the building and covered with dust showed the presence of significant growth of fungi due to the temperature and humidity of the SO_2 chamber. Crystals of gypsum (mainly star shaped or needle shaped) have developed under this organic layer associated with metallic content (mainly iron) and carbonaceous particles. Moreover, the STEM and EDS analysis of the formed black crust and of the accumulated dust on the surfaces of the samples made it quite evident that there was a link between the pollution-derived particulate matter of variable composition and morphology and the presence of high level of other elements besides Fe such as Pb, Cr, Ni, and Co. Moreover, the authors suggested that black crust formation on building materials takes over three main stages as follows:

- Stage 1: dust deposition in the presence of humidity where dust particles retain water from evaporation. This step is further supported by previous works on the role of humidity in the formation of black crust (Haynie 1982).
- Stage 2: catalytic oxidation of SO_2 on the stone surface in the presence of particulate matter and humidity producing gypsum nucleation points as a result of the attack of sulfuric acid on calcite in the limestone as per the following equation:

$$H_2SO_4 + CaCO_3 + H_2O \rightarrow CaSO_4 \cdot 2H_2O + CO_2$$

- Stage 3: As the black crust grow, it forms a discontinuous layer between itself and the unaltered calcareous substrate producing loss of entire slabs of crust and limestone which lead to the growth of gypsum and further development of black crust (Rodriguez-Navarro and Sebastian 1996).

Acidification effect of materials varies with the type of material under investigation. Stainless steels, with alloying elements such as nickel, molybdenum, and chromium, are found to be highly corrosion resistant due to the protective properties of the oxide corrosive films (Bhattacharjee et al. 1999). Aluminum is generally considered resistant to corrosion (Bhattacharjee et al. 1999). On the other hand, stone and cement structures are more susceptible to corrosion because they contain lime. Sulfur dioxide in the acid rain reacts with the calcium in the marble and causes its corrosion. The effect of corrosion is also significant on paints and automobile finishes. Paints are used as decorative coverings or as protective films against the environmental conditions. Paint formulations are not usually resistant to corrosion and hence do not form barriers with SO_2 (Bhattacharjee et al. 1999).

Mitigation policies to control PM concentration in the air

Process management

The role of management to make an actual change to the current situation is critical. Measures such as improved process design, operation, maintenance, housekeeping, and other management practices can significantly reduce emissions (World Bank Group 1998). To achieve an efficient cleaner production program in any facility, data are required to be collected and reported efficiently. One of the increasingly common environmental policy tools for this purpose is the Pollutant Release and Transfer Registers (PRTRs) (Kolominskas and Sullivan 2004). This process requires the support from the management and the collaboration between the producers and decision makers to better design, implement, and monitor cleaner production programs such as the adaptation of a process that would improve combustion efficiency in an industrial facility to minimize the amount of products of incomplete combustion (a component of particulate matter). Proper fuel-firing practices and combustion zone configuration, along with an adequate amount of excess air, can achieve lower products of incomplete combustion (World Bank Group 1998). These practices and changes in process management ensure the continuous application of environmental strategies to increase the overall efficiency and reduce the risk to humans and the environment (Kolominskas and Sullivan 2004).

Eras et al. (2013) demonstrated a quantitative assessment of construction activities where process can be enhanced to reduce three major impacts of earthwork which are related mainly to human toxicity, global warming, and energy consumption. They proposed several cleaner production strategies to reduce the amount of soil used in earthworks, diesel consumption, and the greenhouse gas emissions by 41%. Moreover, those process managements and enhancements have resulted in 1.76 million dollars of savings.

Choice of fuel

Traffic PM and gaseous emissions contribute largely to air pollution worldwide, and despite the technological advancement in developing nanotechnology for PM and gaseous pollutant removal from transport emissions (Isaifan et al. 2015; Merkisz and Pielecha 2015; Isaifan and Baranova 2013), the choice of cleaner fuels for transportation and other activities can extremely reduce atmospheric particulate emissions (Imhof et al. 2005). Natural gas, oil-based processes, and low-ash fossil fuels used as fuels emit negligible amounts of particulate matter (World Bank Group 1998; Blumberg et al. 2003). However, the decision to change the fuel type always depends on the economics and environmental consideration.

In a direct comparison between the effect of diesel versus gasoline fuel for vehicles and their effect on particulate matter emission, Dallmann et al. (2014) measured PM emissions from on-road motor vehicles driving through a highway tunnel in the San Francisco Bay area in 2010. The chemical composition as well as the organic and black carbon fraction of the soot particles were measured at high time resolution. Their finding shows a large fraction of organic carbon in gasoline exhaust is lubricant-derived as well (Dallmann et al. 2014). As a general trend, the increasing influence of gasoline vehicles on the measured organic/black carbon ratio was observed in this study for weekend sampling periods when the influence of diesel trucks was lower (Dallmann et al. 2014).

Recently, several initiatives have been taken to substitute fossil fuels with renewable alternative fuels to reduce greenhouse gas emissions. Bozbas (2008) has investigated the characteristics of biodiesel and its sustainable production for use as a clean fuel. Biodiesel has gained interest recently as a clean fuel due to its environmental benefits especially in Europe. Biodiesel fuel can be made from new or used vegetable oils and animal fats, which are non-toxic, biodegradable, renewable resources. On the other hand, biomass is considered as one of the earliest energy sources being one of the most promising renewable energy sources due to its abundant resources and its environmentally friendly characteristics (El-Shobokshy and Hussein (1993). Nevertheless, Agarwal et al. (2011) have reported in a first study of its kind on the various characteristics and aspects of PM emitted from biodiesel-operated engine compared with those emitted by petroleum-based diesel. The key physical and chemical parameters analyzed included metals, benzene-soluble organic fraction, elemental and organic carbon fractions, particle morphology, particle number, and size distribution. One key difference was that biodiesel and its blends gave more benzene-soluble organic fraction in engine exhaust PM compared with mineral diesel PM at all conditions. Moreover, peak particle concentration for biodiesel was shifted towards smaller size particles. Nevertheless, it was found that the metals that come from engine wear were not present in biodiesel exhaust particulate due to its self-lubricating properties. Those metals have the most negative impact on human health as the use of petroleum-based fuel increases.

Choice of clean technologies and regulatory pressure

Tackling particulate matter pollution is a global as well as a local issue. Therefore, cities and urban areas should implement policies that insist on the importance of the efforts to improve air quality. This is due to the fact that the world population is shifting to urban centers; hence, population will be emitting more PM pollution as well as be more exposed to it. In a recent review by Lyu et al. (2016), the authors conducted detailed index decomposition analysis on the case of air pollution in China. They have reported that current strategies and policies to combat PM emissions are not adequate and provided several sustainable development guidelines to mitigate this issue. The choice of clean technologies for the production of electricity for example would drive a shift in PM emissions from power plants. The use of natural gas and renewable energy alternatives would significantly decline PM emissions as well as other pollutants.

A systematic mapping review conducted by Slovic et al. (2016) evaluated how urban policies improve air quality and help mitigate global climate change by evaluating what policy approaches are more associated with qualitative or quantitative methodologies. It is seen in Fig. 11 that little research has been conducted to look at using regulatory and economic initiatives, although these are of significant importance to environmental urban planning (Slovic et al. 2016).

One of the main mitigation strategies to reduce air pollution and particulate matter especially from the industrial sector is the opt for clean technology or the adaptation of clean process changes in the technology used. Some of the examples that were efficient in reducing PM emissions are the utilization of advanced coal combustion technologies such as coal gasification and fluidized-bed combustion in addition to the incorporation of coal crushers and grinders, which all proved to be enhancements of technologies as cleaner processes that reduced PM emissions by approximately 10% (World Bank Group 1998). Some corrective measures can have tremendous effect on reducing PM emissions such as regulating chipping and grinding operations, modifying cement kilns to reduce PM emissions, and encouraging the purchase and operation of gasoline-driven machines over diesel-driven to minimize PM. One of the effective regulatory proposals for employers who hire more than 250 employees to be encouraged is to arrange for their transportation to reduce mobile source emissions.

In another example, Driussi and Jansz (2006) have presented several technological options to minimize waste production in mining industry. Mining activities are among the most polluting processes in terms of air, waste, noise, and ecological pollution. For air pollution reduction in such sites, the authors recommended applying water on roadways, constructing enclosures over conveyors, and limiting free fall of rocks. They also recommended the use of specialized machines to remove dust particles from emissions. These machines include the use of centrifugal force cyclones, gravity settling chambers, and electrostatic precipitators as shown in Figs. S4 and S5 (Ligocki et al. 1993), respectively.

Moreover, a recent study has targeted the green building design implementations through a review that elaborates on the influential parameters on their impact on sustainable development (GhaffarianHoseini et al. 2013). As a result, the analytical review confirms that the sustainable energy performance of green buildings has been transformed to a sensible and practical resolution to air pollution problems including PM and CO_2 emissions. Nevertheless, there are still challenges and barriers that are crucial to identify and develop efficient energy solutions associated with green buildings for addressing the future energy demands (GhaffarianHoseini et al. 2013).

Plantations and urban vegetation

Several researchers have reported on the impact of tree and plants from an indoor and outdoor air quality perspective (Gawronska and Bakera 2015; Isaifan et al. 2018, b; Tong et al. 2017). Urban vegetations have proven to impact our ecosystem positively by providing scenic public landscape, reducing flooding consequences, reducing the use of fossil fuels for heating, and cooling in addition to the filtration of airborne particulate matter (Bell and Jayne 2009).

Janhäll (2015) has reviewed the deposition and dispersion of particulate air pollution by urban vegetation. Deposition of particulate matter on vegetation is usually described as one-dimensional vertical deposition on a homogeneous layer of vegetation in the form of a forest or field. Most plants have a large surface area per unit volume, increasing the probability of deposition compared with smooth, manufactured surfaces present in urban areas. The review has revealed that the design and choice of urban vegetation are crucial when plants are used as an ecosystem service for air quality improvements. More specifically, adding large trees in trafficked streets with reduced mixing has increased local air pollution levels. On the other hand, low vegetation placed close to air pollution sources has improved air quality through increasing deposition. Another parameter that should be considered in planning urban vegetation is filtration vegetation barriers. Those are recommended to be dense enough to offer large deposition surface area and should be porous to allow penetration instead of deflection of air stream above the barriers. In addition, the choice between tall or short and dense or sparse vegetation determines the effect of air pollution from different sources as well various particle sizes (Janhäll 2015).

Maher et al. (2013) studied the impact of planting silver birch trees on the levels of PM at a city block in Lancaster City in the UK. They found that those trees have absorbed as much as 50% of the PM generated by vehicles in the street. The detailed investigation of silver birch leaves using scanning electron microscopy (SEM) has revealed that the presence of tiny hair-like structures on the surface of those leaves was responsible for removing the particulate from the air.

In a recent study reported by Gourdji (2018) in Quebec, Canada, the different green roof categories and plants were reviewed for their capabilities to reduce particulate matter, ozone, and nitrogen dioxide levels. It was found that green roofs with larger vegetation that include shrubs and trees or intensive green roofs remove air pollutants to a great extent. Pine trees were also found to be most effective for PM removal and hence are considered good candidates for intensive green roofs. On the other hand, broad-leaved trees such as Japanese maple are drought tolerant and have low biogenic volatile organic compounds emissions and hence considered good options for ozone level reductions. Moreover, magnolia trees were found to be tolerant to nitrogen dioxide removal as the latter are essential for the plants' metabolic pathways.

Mitigation of dust and particulate matter in desert areas is of critical importance to reduce their impact on PV surfaces as well as building and other materials present in the cities. Studies have shown that trees can directly affect particulate matter concentration in air through three main routes: (1) by removing particles, (2) emitting particles, or (3) by the resuspension of particles on the surfaces of these trees (Mell et al. 2010; Nowak 2000).

In a recent study by Isaifan et al. (2018), the authors reported on the evaluation of economic and environmental benefits of planting three abundant urban tree species in the State of Qatar. The trees that were investigated (*Acacia*, *Ziziphus*, and *Phoenix dactylifera*) grow naturally in desert areas and require minimum rain and care. The environmental economic value of these species was found to be the highest for *Acacia*, followed by *Ziziphus* and then *P. dactylifera* which is in agreement with their Air Pollution Tolerance Index (APTI). The APTI is a factor used by researchers to assess the tolerance of trees to air pollution, the higher the APTI, the less sensitive the species to pollution. Hence, those studies indicate that, in order to have adequate, green infrastructure-based policies to mitigate air pollution in cities, urban planning that include vegetation should be implemented at lager scales.

Critique

The research reviewed in this work has highlighted the knowledge that has been reported on the impact of particulate matter on materials and welfare of human beings. It focused on the adverse impact of PM on solar panel efficiency and power output, climate change, acid rain, and visibility, as well as on heritage and cultural buildings. Nevertheless, there are still several gaps that prevail in this domain. The following are some suggestions for researchers to consider for future research work:

– Characterization and source apportionment of airborne PM are not adequately studied in some parts and countries in the world. More specifically, in the countries of Arabian Gulf, only one study was found on the characterization of particulate matter with significant findings and discussions to identify the sources of these particulates. Source apportionment of PM is of critical importance for researchers and decision makers to abate anthropogenic activities and impose control measures to reduce harmful PM.
– An in-depth research to evaluate the impact of PM on the economics from an environmental perspective should be conducted. This field lacks input and contribution in most countries around the world. The study that was published to evaluate policy changes in the state of NY and the connection made to the impact of this change on PM and gaseous pollutant emission levels indicates that economics and environment are not separable. In addition, it is not feasible to impose economic models developed for certain societies to other cities and countries as each place has its own economic and environmental conditions and should be studied on its own.
– Taking into consideration the importance of developing efficient energy solutions that meets our current and future energy demands, it is of critical importance that the impact of PM on the efficiency and power output of renewable energy options such as solar power and wind power should be investigated. Moreover, solutions to mitigate PV soiling by PM should align with the environmental conditions in each geographic location. A specific example is the development of hydrophilic vs. hydrophobic anti-dust coatings for regions with low/high rainfall and/or the development of feasible PV cleaning strategies and technologies to ensure efficient and cost-effective PV installations.
– There are only few studies conducted to develop economic models to assess the losses associated with PM deposition on PV panels. The evaluation of traditional options such as manual cleaning or cleaning with water or detergents should be evaluated to assess the overall benefits and feasibility of solar energy deployment as an option or solution for energy shortage in desert areas.
– This research has drawn attention to the importance of frequent investigation of the status and condition of heritage and cultural building. Access and approval to examine heritage and historical buildings might not be guaranteed. Hence, collaborations between research, government, and stakeholders among public awareness are all critical parameters for a sustainable environment in the field of PM pollution abatement.
– There is a need for studies related to the impact of intervention and public awareness programs to minimize the adverse effect of PM on materials, buildings, walls, cars, solar panels, etc. similar to the evaluation of programs that spread awareness to face the adverse impact of PM on human health. Collaboration between research and governments in this regards is essential for speedy process to save losses in human welfare and belongings prone to PM impact.

Conclusion and future work

When the health effects of particulate matter have been confirmed to cause severe diseases that can lead to human mortality, increasing attention has been paid to understand the chemical composition, sources, and effect of PM on our health and ecosystem. Hence, extensive efforts and research have been published to evaluate PM impact on health. Nevertheless, the effect of PM on material has mainly been investigated in the field of PV panel soiling. PV soiling of solar panels has caused tremendous loss in the output power which is considered a main obstacle towards the efficient implementation of solar energy in many areas around the world. Therefore, this paper shed light on the impact of particulate matter on solar panels, materials, buildings, and heritage structures. The findings of this narrative literature review reveal that indoor and outdoor particulate matter has tremendously affected several structures by darkening their colors, reducing glass reflectance and lightness, and increasing the overall corrosion rate. As PM pollution is found to be more critical in cities and urban areas, several mitigation strategies have been suggested to preserve sustainable environment and reduce the loss of materials' value and lifetime. One of the sustainable policies that have shown a promising effect on the reduction of PM concentration in the cities is the choice of green fuels as well as considering urban vegetation for air pollution control. Nevertheless, it should be always taken into consideration that policies should be firm and stringent to implement corrective actions especially at the commercial and industrial level.

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Compliance with ethical standards

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