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Review

A Comprehensive Review of PM-Related Studies in Industrial Proximity: Insights from the East Mediterranean Middle East Region

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Abstract: This comprehensive review synthesizes the current knowledge regarding the characteristics of particulate matter (PM) at locations directly impacted by industrial emissions. A particular emphasis was given to the morphology and size of these particles and their chemical characteristics per type of industrial activity. The relationship between the exposure to PM from industrial activities and health issues such as cancer, cardiovascular, and respiratory diseases was also discussed, highlighting significant epidemiological findings. Furthermore, this work highlights the source apportionment of PM in these areas as well as available databases for source profiles. The majority of the studies accentuate the ambiguity found in the identification of industrial sources mainly due to the lack of specific tracers and the overlapping between these sources and other natural and anthropogenic ones. The contribution of industrial sources to PM concentrations is generally less than 10%. Moreover, this review gathers studies conducted in the 18 countries of the East Mediterranean-Middle East (EMME) region, focusing on sites under industrial influence. In these studies, PM₁₀ concentrations range from 22 to 423 µg/m³ while PM_{2.5} levels vary between 12 and 250 µg/m³. While extensive studies have been conducted in Egypt, Iran, and Lebanon, a lack of research in the UAE, Bahrain, Greece, Israel, Palestine, and Yemen highlights regional disparities in environmental health research. The major industrial sources found in the region were oil and gas industries, metallurgical industries, cement plants, petrochemical complexes, and power plants running on gas or heavy fuel oil. Future research in the region should focus on longitudinal studies and a more detailed chemical analysis of PM in the vicinity of industrial areas to enhance the accuracy of current findings and support effective policy making for air pollution control.

Keywords: PM; industrial complexes; chemical characterization; source apportionment; EMME region



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1. Introduction

Air pollution, traced back to as early as 400 BC during the time of Hippocrates, has long been identified as a threat to human health [1]. In the era of rapid industrialization, the world has witnessed a substantial upswing in economic prosperity and an enhancement of living standards. Nevertheless, this progress has been accompanied by a growing environmental imbalance, and the start of a drastic degradation of the air quality.

Pivotal technological advancements, such as the invention of steam power, refinements in iron-making techniques, transformative shifts in the textile industry, the widespread adoption of coal to replace wood, the integration of fuel oil combustion, and other substantial modifications, have markedly reshaped the industrial sector. The consumption of

fossil fuels worldwide has amplified since the industrial revolution in the XXth century and contributed to the increase of sulfur and carbon emissions [2]. General media have reported that the global petrochemicals market size is still increasing at a compound annual growth rate of 8.5% with a projection to reach USD 958.8 billion by 2025 [3]. Furthermore, the concern regarding the effects of air pollution on human health has returned as a significant priority towards the end of the XXth century and the beginning of the XXIst century as epidemiological studies started to emphasize the association between human mortality and morbidity with the levels of air pollutants in the atmosphere [1,4]. These historical developments set the stage for today's environmental policy challenges, where the need to balance industrial growth with public health and environmental sustainability has become increasingly vital. Achieving this balance is crucial for sustainable development, as clean air is essential for both humans and ecological stability. Air quality policies must therefore prioritize reducing emissions while supporting economic growth, ensuring a healthier environment for current and future generations.

Industrial areas encompass a considerable number of industries, sharing common infrastructures (transport networks, wastewater treatment plants, waste incineration plants, etc.). These areas aggregate high-risk activities and sources of pollution, but are still attracting hundreds of employees who have settled in the vicinity of these plants and are at high risk of exposure [5]. Moreover, with urbanization and industrialization reaching unprecedented proportions worldwide, industrial areas have become embedded in the urban landscape, amplifying both nuisances and population exposure [6]. According to Mannucci and Franchini [7], if the exposure to industrial air pollution is considered to be a serious threat in developed countries, the problem is even more serious in developing countries due to overpopulation and uncontrolled urbanization, coupled with widespread industrialization, and the lack of clear standards regarding pollutant emissions. This leads to poor air quality especially in countries where huge economic and social disparities exist.

According to the World Health Organization (WHO), nitrogen oxides (NO_x), sulfur dioxide (SO₂), carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter (PM) are considered to be classic air pollutants found in industrialized countries [8]. Moreover, with the increasing impact of atmospheric particles on human health, the focus of the studies shifted from pollutants, such as SO₂ and NO₂, to particles, which were classified by the International Agency for Research on Cancer (IARC) in 2013 as Group 1 "carcinogenic to humans" [9]. PM is defined as a mixture of solid particles and liquid droplets in the atmosphere [10]. Numerous scientific studies have linked particle exposure to a variety of health issues, including premature death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function, and increased respiratory symptoms like airway irritation, coughing, or difficulty breathing [11]. Moreover, recent meta-analysis studies have shown that long-term exposure to PM₁₀, PM_{2.5}, and PM₁ was related to cardiovascular and respiratory diseases [12]. The size, composition, and origin of PMs influence their pathogenicity [13]. Therefore, as the particles decrease in diameter, their potential health risks become more pronounced. Coarse particles (PM_{2.5-10}) generally deposit in the upper respiratory tract while fine (PM_{2.5}) and ultrafine (PM_{0.1}) particles can penetrate deeply into the lungs, reaching the alveolar region and bloodstream, where air pollutants and nanoparticles have a direct influence on human health [14]. According to Lelieveld et al. [15], the total number of excess deaths attributable to fine particulate and ozone air pollution is estimated to be 8.34 million annually. The major proportion of these deaths is caused by anthropogenic emissions, of which 82% is attributable to the usage of fossil fuels in industries, power generation, and transportation globally. Besides industrial sources, PM can also originate from a variety of anthropogenic sources: solid-fuel combustions such as coal, lignite, heavy oil, and biomass, agricultural operations, road traffic erosion, and brake and tire abrasion, as well as natural sources such as volcanoes, dust storms, forest fires, living vegetation, and sea spray [16–18]. The chemical characterization of particles collected in the vicinity of industrial areas is variable, complex, and highly dependent on the type of industrial activity in the nearby area [19].

Previous reviews on PM emissions from industrial complexes have examined the health impact of air pollution around major industrial areas [3,5,20], the characterization of fine and ultrafine particles near industrial complexes [19], and the use of receptor modeling, to analyze industrial PM emissions [21].

The East Mediterranean- Middle East (EMME) region is considered to be a hotspot for climate change [22]. The Emissions Database for Global Atmospheric research (EGDAR version 6) showed a considerable increase in atmospheric pollutants emissions from anthropogenic sources in the EMME region between 1970 and 2018 [23]: from 1.4% to 8.6% of global SO₂ emissions, from 1.8% to 7.7% of global NO_x emissions, from 1.0% to 1.9% of global PM_{2.5} emissions, and from 1.4% to 2.2% of global CO emissions. Hence, by the end of the century, model projections point to this region as one of the regions with predicted gradual warming and a predicted drying climate [24]. Located at an atmospheric crossroads, this region is impacted by a variety of atmospheric circulation patterns and meteorological processes originating from different continents [25]. In this region, the climate is highly diverse, characterized by temperate temperatures in the north with hot, dry summers and relatively mild winters. Conversely, the southern areas experience desert-like conditions, marked by dry, scorching weather and a scarcity of vegetation and rainfall [26]. Furthermore, the region is subject to environmental and social problems due to rising needs for industrial production, as well as urbanization [27]. Many factors lead to industrial pollution, including manufacturing techniques, a lack of abatement equipment, insufficient environmental rules, and a lack of social awareness for environmental protection [27]. The characterization of atmospheric aerosols in this area remains incomplete, especially in industrial zones. Thus, a more critical analysis regarding industrial pollution covering the most industrialized countries in the EMME region is mandatory.

The aim of this review article is to present the current state of knowledge regarding the physico-chemical properties of particles collected in the proximity of different types of industries, the health effects for the population affected by this pollution, and the use of industrial marker species in the source apportionment studies. A special emphasis is given for studies conducted in the EMME region that focused on PM released by industrial emissions. This paper will also help identify knowledge gaps and scientific challenges in this domain in order to provide valuable insights for policymakers to develop regulatory suggestions for industries and to enhance air quality within the EMME region and worldwide.

2. Physico-Chemical Characterization of Particles Emitted by Industrial Sources

2.1. Morphology and Size of Particles

Particles in the atmosphere differ in various physical properties. In this work, we will focus on differentiating particles emitted by industrial activities based on their size and morphology: tar balls, soot, fly ashes, and metallic particles [19]. It is worth noting that these particles might also be emitted by other anthropogenic sources.

Soot particles, also known as black carbon aerosols (BC), show a diameter between 30 and 150 nm and mainly originate from the incomplete combustion of fossil fuels by combustion engines, biofuel, coal, and biomass [28–30]. Regardless of their emission sources, they consist of a graphitic part (elemental carbon) on which functional groups are chemically bonded and a second part consisting of organic compounds such as polycyclic aromatic hydrocarbons (PAHs) and their derivatives [31]. Upon emission, individual soot particles consist of multiple nanocarbon spheres called soot aggregates (Figure 1a). They commonly interact with organic and inorganic materials during the combustion or atmospheric aging process, transforming their morphology from a chain-like to a compact structure [32]. BC strongly absorbs solar radiation and significantly influences regional and global climate since it is considered to be the second largest global warming agent after CO₂ [33].

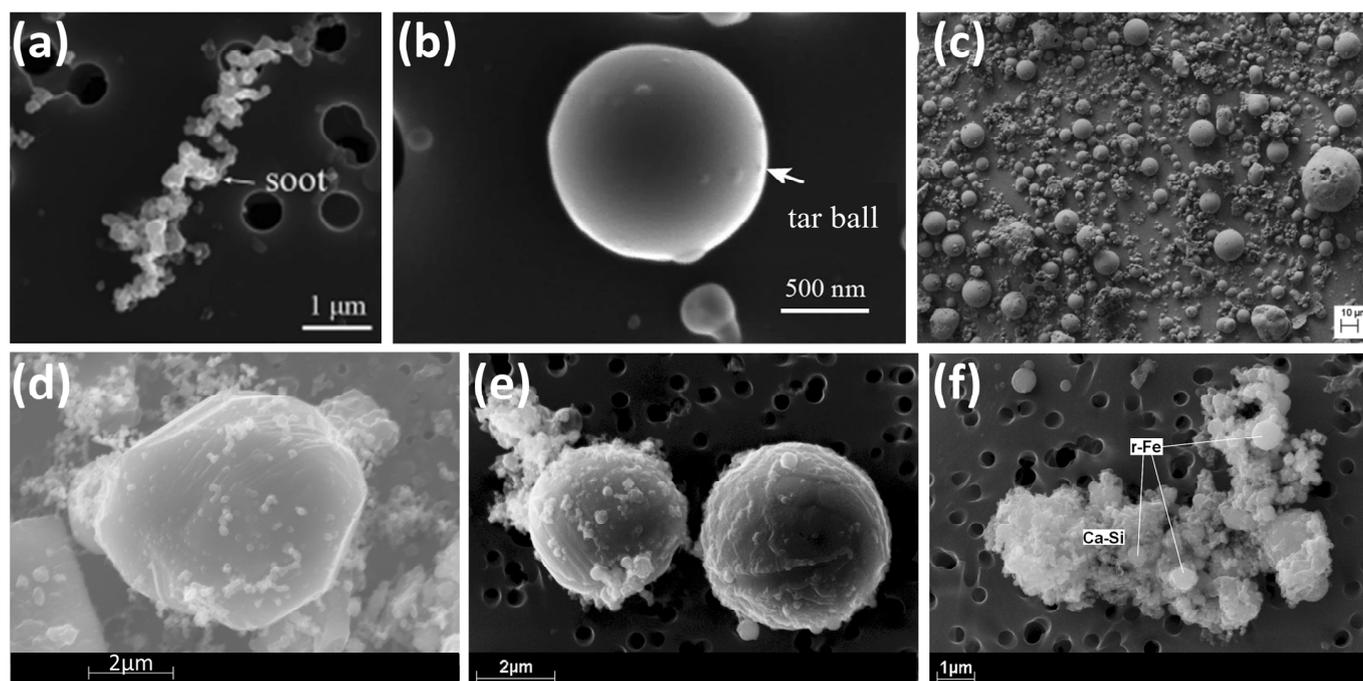


Figure 1. SEM images of the different morphology of particles: (a) chain-like soot aggregates [34], (b) tar ball collected in suburban air [34], (c) spherical particles in traditional pulverized coal combustion fly ash [35], (d) Fe ores with angular shape [36], (e) Fe spheres, and (f) agglomeration of Fe with Ca and Si particles in dust samples collected from fugitive emissions in the steelmaking process [37].

Tar balls, a type of brown carbon (BrC), are significant due to their ability to absorb light and affect the Earth's radiative balance. They are found in the global troposphere and are particularly abundant in slightly aged biomass smoke (minutes to hours old), but can also originate from biofuel burning [28,38,39]. However, due to their coexistence with various other particle types from which they cannot be physically separated, the extent of their impact remains highly uncertain [40,41]. They are highly viscous, amorphous, carbonaceous spherules with a geometric diameter between 30 and 500 nm (Figure 1b) [28,41]. Tar balls can be identified by transmission electron microscopy (TEM) based on their morphology and their amorphous structure, while they can be chemically characterized by TEM-EDS (TEM with energy-dispersive X-ray spectroscopy) or TEM-EELS (TEM with electron energy-loss spectroscopy) [40,42]. It is worth noting that other carbon-rich particles emitted during industrial activities can also correspond to coal and coke particles used, combustibles, and/or reducing agents [43,44]. Graphite flakes can also be found in industrial fugitive emissions [37,45].

Unlike soot particles, which are primarily composed of carbon, fly ashes contain a diverse array of minerals, making them more complex in terms of chemical behavior and health implications [46]. They are considered to be important industrial byproducts, accompanying different industrial sectors such as energy production by fossil fuels, particularly coal combustion, cement, and titanium oxide industries [47]. They consist of an amorphous mixture of ferro-aluminosilicate minerals with varying compositions in the elements, depending on the type of the fuel used and the method of production (Figure 1c). For instance, fly ashes generated from coal combustion mainly contain oxides such as SiO_2 , Al_2O_3 , Fe_2O_3 , and CaO [47]. According to Li et al. [48], the particle size of fly ashes is important since fine-sized fly ashes are more persistent than coarse fly ashes and may cause several cardiovascular diseases. The particle size for coal fly ashes varies between 0.3 and 250 μm with a bimodal distribution where the maxima peaks occur at 0.5–0.6 μm and 20–25 μm . The formation mechanism of these two particle sizes is different. The formation of the 0.5–0.6 μm particles is mainly due to the vaporization, condensation, and nucleation of the mineral matter in the fuel gas and such particles contain a group of refractory oxides of

major elements such as K, Na, S, Cl, Zn and in some cases P. Bigger particles (20–25 μm) are produced from the fusion and coalescence of inorganic material on the surface of burning particles. Particles with a diameter higher than 10 μm contain mainly refractory metals such as Ca, Mg, Mn, and Si [48,49].

Metal oxide-based particles are generally emitted by metallurgical activities. Depending on the step of the industrial process, these metal oxide particles can be found in the form of angular (Figure 1d), spherical-shaped particles (Figure 1e) or aggregates (Figure 1f) [43]. They can also be emitted after the handling of metal oxide ores and sintering and might have different shapes. According to Moreno et al. [50], iron particles emitted from steel industries mainly result from the condensation of iron released into the atmosphere during high-temperature processes. These iron particles are mostly spherules with a size less than 2 μm and either can agglomerate to form bigger particles or stay as individual particles [37,45,50].

2.2. Chemical Characteristics of Particles Emitted from Different Types of Industries

The chemical composition of atmospheric particles emitted from industrial processes is complex and highly variable depending on the type of industry, process, fuel used, common practices, etc. In this paragraph, we will be presenting the source tracers found in the literature per type of industry.

2.2.1. Coal-Related Industries

The major pollutants released by coal-related industries are particulates, sulfur and nitrogen oxides, combustion trace elements (Cs, F, Se, Hg, and the radionuclides U and Th), and organic compounds produced by incomplete coal combustion, such as PAHs [51,52]. In addition to these trace elements, Han et al. [53] reported that coal combustion processes emit several trace elements including As, Pb, and Zn, which are the major constituents of coal, while Wang et al. [54] also added Cd and Cr. Moreover, each geographical region worldwide possesses a distinct coal composition influenced by the peat depositional settings, as indicated by Dai et al. [55]. For instance, the coal used in India and China contains high amounts of Hg, resulting in high levels of emissions of Hg in these countries [56,57]. In South Africa, significant amounts of Pb were found near coal-fired power facilities [58]. When Brazilian coal is burned, it emits significant quantities of As and Zn [59]. According to Tian et al. [60], the distribution of n-alkanes emitted from coal combustion processes showed peaks at C_{16} – C_{18} and C_{22} – C_{25} . Additionally, the hopane concentration ratio of $17\alpha(\text{H}),21\beta(\text{H})\text{-}30\text{-norhopane}(\text{C}_{29\alpha\beta})/17\alpha(\text{H}),21\beta(\text{H})\text{-}30\text{-hopane}(\text{C}_{30\alpha\beta})$ is higher than 1 for coal sources, while it is less than 1 for road traffic emissions. Fluoranthene and pyrene were mostly used as indicators of emissions from coal combustion [60].

2.2.2. Steel and Metal Industries

Steel and metal processing provided significant releases of trace elements in the atmosphere. PM emissions mainly originate from high-temperature processes such as sintering, blast furnaces, and steelmaking [37]. The chemical profiles for samples taken near these industrial facilities showed a considerable contribution of elements including As, Cd, Cr, Fe, Mn, Ni, Pb, Sb, and Zn [36,37]. In addition, Fe, Zn, Cr, Cu, Mn, Ni, and Pb might be emitted from the electric arc furnace of steel industries [61–63]. Moreover, Hleis et al. [37] highlighted that crustal elements such as K, Fe, Ca, and Al may also be involved with industrial activities, most notably metallurgy and sintering processes. Furthermore, Ca, Cu, Mn, and Pb are elements derived from industrial operations such as Cu smelting (Cu, Ca, Pb) or steel factories (Ca, Mn, Cu) [64]. Zn and Cu were found to be significant components released by the local nonferrous metal industry [65]. As for PAHs, they are mainly sourced from the sintering process with an abundance of four- to six-rings compounds such as fluoranthene, pyrene, chrysene, benz[a]anthracene, dibenz[a,h]anthracene, and benzo[g,h,i]perylene [66]. On the other hand, Cetin et al. [67]

have reported that acenaphthylene, anthracene, fluorene, phenanthrene, pyrene, and benz[a]anthracene were emitted during iron and steel production.

2.2.3. Oil Combustion

Oil combustion, which is linked to petroleum refining, petrochemical-related industrial complexes, and ship emissions at the port, has revealed high contributions of V, Ni, and SO_4^{2-} [68,69]. Additionally, Co was reported to also be linked to heavy fuel oil burning [70]. Lin et al. [61] found that total suspended particle emissions from oil refineries include Ni, Sb, La, Co, and V, while Chow et al. [71] reported V, Ni, La and Sb for $\text{PM}_{2.5}$ emissions. Moreover, chrysene is predominantly released from industrial oil burning [72]. Ma et al. [73] reported that PAHs and nitrated-PAHs (NPAHs) may be linked to oil and petrochemical industry emissions. During the refueling and transportation process, low molecular weight (LMW) PAHs including two- and three-ring PAHs can be volatilized at petrol stations, and petrochemical and oil refinery plants [74].

2.2.4. Cement Manufacturing Industries

PM can be released from various stages of cement production, including kilns, fugitive emissions from raw materials, and the processing of these materials in quarries [75]. The PM speciation profiles for cement manufacture from the United States Environmental Protection Agency (USEPA) SPECIATE 5.1 database reveal high levels of K, Ca, S, K^+ , Cl^- , NO_3^- , SO_4^{2-} , and OC [76]. Ca^{2+} , Mg^{2+} , K^+ , PO_4^{3-} , and SO_4^{2-} , are soil constituents, and the majority of these species also occur as raw materials in cement plants or fertilizer companies [77,78]. According to Lin et al. [61], cement plants emit Tl, Cs, Rb Ca, and Sr found in total suspended particles, while Bano et al. [79] reported Al, Ca, Cu, and Mg for $\text{PM}_{2.5-10}$, and Kong et al. [80] presented high levels of Zn, Mg^{2+} , SO_4^{2-} , Ca, and Mg in PM_{10} . As for PAHs, the indicator PAHs of cement plant emissions were acenaphthylene, acenaphthene, and anthracene (three-rings PAHs) [74,81].

2.2.5. Glassmaking Industries

PM can be emitted by the melting of raw materials, additives, or colorants in the oven [70]. The particles emitted from heavy glassmaking factories are mainly enriched with elements such as Al, Ti, Ca, Mg, Fe, Mn, Sr, Rb, and Ba, which are known to be the major components of the raw materials in glassmaking factories [82]. Additionally, Li, Zn, As, Se, Cd, Sb, and Pb can be emitted from this type of industry and might come from the usage of refining additives and/or colorants [83,84]. Ledoux et al. [70] reported Sn, As, Cu, and Cr in $\text{PM}_{2.5}$ for the glassmaking industry, and established diagnostic ratios in order to further understand and distinguish between anthropogenic sources particularly for industrial sources, specifically for the glassmaking industry, by combining typical concentration ratios ($\text{Sn/Sb} = 6$, $\text{Sn/Cr} = 13$, $\text{Zn/Mn} = 13$, $\text{Cu/Cd} = 17$, $\text{Pb/Cd} = 36$, $\text{As/Ag} = 37$, $\text{Pb/Rb} = 44$).

2.2.6. Plasticizing Industries

Chemicals used in plasticizing industries, such as phthalates, are hazardous to human health. In fact, many different phthalic acid esters (PAEs), present in a wide range of industries, including personal care products such as perfumes, lotions and cosmetics, paints, industrial plastics, certain medical devices, and pharmaceuticals, are primarily used to improve the durability and flexibility of plastic products like monomeric plasticizers [85–87]. More precisely, dibutyl phthalate (DBP) is commonly utilized as an additive in the production of polyvinyl chloride polymers (PVC) in order to make them more flexible in industries [85]. Di-n-butyl phthalate (DnBP), diisobutyl phthalate (DiBP), and di(2-ethylhexyl) phthalate (DEHP) are common additives in plastics and other commercial products [88].

2.2.7. Other Types of Industries

Construction activities are considered to be an important source of emissions for different metallic elements such as Al, Fe, Si, Mn and Ti in the form of aluminosilicates [89]. Additionally, Azarmi et al. [90] have estimated the exposure of workers to PM during refurbishment tasks and found that they are mainly exposed to hazardous elements, such as Al, Zn, Ca, Cu, S, Si, and K. S, Mo, and Br were utilized as tracers of oil sands industry emissions [91]. Particles from waste incineration are characterized by high levels of Pb, Zn, Hg, Cl⁻, dioxins, furans, and polychlorinated biphenyls [19,92]. PAHs can be caused by industrial waste from large and small industries and factories such as petrochemical processes, gas refinement, stone crushing, electronic/electrical component factories, industrial equipment repair workshops, plastic pipe industry, packaging industry, etc. [93]. High-temperature activities such as thermal power plant operations may be one of the causes of medium to high molecular weight PAH emissions three- to six-ring PAHs [94].

Industrial emissions might also contribute to the formation of secondary organic compounds in the atmosphere, especially in the vicinity of those that produce enormous amounts of key precursors of VOCs, such as automobile manufacturing industries and crude oil industries [53].

3. Health Effects for the Population Living in the Vicinity of Industrial Complexes

Residents near major industrial areas are facing different exposure situations: occupational and environmental exposure, exposure to a wide range of chemicals, and exposure to visual pollution, dust, stress, and noise. According to Pascal et al. [5], quantitative health risk assessments that involve comparisons between measured or modelled concentrations to toxicological reference values, have been widely employed for regulatory purposes. However, this type of assessment faces limitations, especially in determining the actual number of people suffering because of the pollution and in considering the integrated burden of the multi-exposure to chemicals. That is why epidemiological studies should be well-designed in order to try to answer these questions. Several studies in the literature have tried to investigate the health impacts of air pollution around industrial areas. These studies were either motivated by concerns of the population or by previous observations of an over incidence of health outcomes. The major health themes investigated were cancers, morbidity, mortality, and birth outcomes [5]. A list of studies evaluating the carcinogenic and non-carcinogenic effects for the population living in the vicinity of industrial complexes is presented in Table 1.

Table 1. List of epidemiological studies evaluating the carcinogenic and non-carcinogenic effects for the population living in the vicinity of industrial complexes.

Study Reference	Location/Period of Time	Age Category	Type of Close Industries	Observation	Ratios
Carcinogenic effects					
García-Pérez et al. [95]	Spain 1996–2011	Children (0–14 years)	Glass and mineral fibers, production and processing of metals, galvanization, and surface treatment of metals industries.	Excess risk of leukemia	Odds ratio (OR) = 1.31; 95% Confidence interval (CI): 1.03–1.67
García-Pérez et al. [96]	Spain 1994–2003	Overall population	Industrial combustion installations	Excess mortality for lung cancer	Risk Ratio (RR) = 1.066; 95% CI: 1.041–1.091
				Excess mortality for laryngeal cancer in men	RR = 1.067; 95% CI: 0.991–1.148
López-Cima et al. [97]	Spain 2000–2008	Overall population	Metal industries, coal mining facilities, and fossil-fuel-fired power plants	Excess risk of lung cancer	OR = 1.49; 95% CI: 0.93–2.39
Edwards et al. [98]	England 2000–2004	Women aged less than 80 years	Steelworks, chemical plant and refinery complexes, chromium works	Excess risk of lung cancer	OR = 1.83; 95% CI: 0.82–4.08
Yang et al. [99]	Taiwan 1990–1994	Female	Petrochemical manufacturing industries	Higher risk of developing lung cancer	OR = 1.66 95% CI: 1.05–2.61
Tsai et al. [100]	Taiwan 1995–2005	Overall population	Petrochemical manufacturing industries	Higher risk of death attributable to bladder cancer	OR = 1.48 95% CI: 1.10–1.99
Non-carcinogenic effects					
Alwahaibi and Zeka [101]	Oman 2006–2010	Children (0–20 years)	Petrochemical, oil refinery, and iron smelter industries	Acute respiratory diseases	RR = 2.5 95% CI: 2.3–2.7
				Conjunctivitis	RR = 3.1 95% CI: 2.9–3.5
				Asthma	RR = 3.7 95% CI: 3.1–4.5
				Dermatitis	RR = 2.7 95% CI: 2.5–3

Table 1. Cont.

Study Reference	Location/Period of Time	Age Category	Type of Close Industries	Observation	Ratios
Yang et al. [102]	Taiwan 1996	Adults (30–64 years)	Petrochemical industries	Acute irritative symptoms (eye irritation, nausea, throat irritation, and chemical odor perception)	-
Svechkina et al. [103]	Israel 2015	Newborns	Petrochemical industries	Association between low-birth weight rate and the proximity to industries	B (Unstandardized regression coefficient) = -0.26 ; 95% CI: -0.30 – -0.22
Eom et al. [104]	Korea 2012–2015	Adults (20 years and older)	Petrochemical, automobile, high-tech, steel, shipbuilding complexes, etc.	Cough	OR = 1.18; 95% CI: 1.06–1.31
				Sputum production	OR = 1.13; 95% CI: 1.03–1.24
				Symptoms of atopic dermatitis	OR = 1.10; 95% CI: 1.01–1.20
Bergstra et al. [105]	The Netherlands 2012–2017	Overall population	Large petrochemical factory, fertilizer factories, a bromine plant, and terminals for storing and shipping of dry bulk products, including among others, fertilizer.	Significant association between PM ₁₀ levels and medication for cardiovascular diseases	OR = 1.06; 95% CI: 1.06–1.06
				Significant association between PM ₁₀ levels and medication for inflammatory conditions	OR = 1.05; 95% CI = 1.00–1.09
Bergstra et al. [106]	The Netherlands 2012	School children (7–13 years)	Power plant, terminals for storing coal, plastic recycling company, oil refinery	Significant association between the exposure to PM _{2.5} and decreased lung function	B = -2.8% ; 95% CI: -5.05% to -0.55%

Marquès et al. [3] and Domingo et al. [20] have reviewed epidemiological studies presenting the health risks associated with people living near petrochemical complexes and oil refineries. Domingo et al. [20] have gathered up to 23 investigations aiming at assessing whether there is a correlation between residing in the vicinity of these types of industries and a higher incidence of cancer and cancer mortality. Particularly, studies conducted in Taiwan, Spain, the United Kingdom, Italy, and Nigeria identified leukemia and other hematological malignancies as predominant cancer types among these populations [95,107–110]. For instance, the study conducted by García-Pérez et al. [95] has found that an excess risk of leukemia was observed for children living near industries (odds ratio, OR = 1.31; 95% confidence interval, CI = 1.03 to 1.67), particularly glass and mineral fibers, production and processing of metals, galvanization, and surface treatment of metals industries. Furthermore, other studies conducted in Taiwan, Italy, United Kingdom, Spain, and the United States of America (USA) [96–100,111] have reported an increased occurrence of lung and bladder cancer in the overall population. García-Pérez et al. [96] have shown that an excess mortality for lung cancer was detected for the overall population living near industrial combustion installations (risk ratio RR = 1.07; 95% CI 1.04 to 1.09). In the latter study, the excess mortality rate for lung cancer was observed for all types of fuel used whereas for laryngeal and bladder cancers, the excess rate was mainly associated to coal-fired industries.

On the other hand, Marquès et al. [3] have reviewed papers related to the non-carcinogenic effects associated with populations living next to petrochemical complexes. The majority of the studies reported increases in the prevalence of the investigated health effects, especially asthma and other respiratory problems, among children and adults, as well as reproductive outcomes in pregnant women. For instance, Alwahaibi and Zeka [101] have reported that children younger than 20 years old and living within 10 km of an industrial park (petrochemical, oil refinery, and iron smelter industries) in Oman showed higher acute respiratory diseases (RR = 2.5; 95% CI = 2.3 to 2.7), conjunctivitis (RR = 3.1; 95% CI = 2.9 to 3.5), asthma (RR = 3.7; 95% CI = 3.1 to 4.5), and dermatitis (RR = 2.7; 95% CI = 2.5 to 3) when compared to the control zone. Yang et al. [102] have found that adults (436 adults aged between 30 and 64) living in a petrochemical-polluted area in Taiwan were more affected by acute irritative symptoms (eye, nausea, throat irritation, and chemical odor perception) compared to the reference area. The closeness of the residential areas to petrochemical industries in Israel was also associated with a low-birth-weight rate ($B = -0.26$; 95% CI = -0.3 to -0.22) [103]. Moreover, a study conducted by Eom et al. [104] for a population living near industrial complex areas in Korea (petrochemical, automobile, high-tech, steel, shipbuilding complexes, etc.) showed that the residents have a higher prevalence of respiratory symptoms such as cough and sputum production, as well as symptoms indicative of atopic dermatitis. Additionally, the prevalence of lung and uterine cancer was, respectively, 3.45 and 1.88 times higher compared to residents in the control area.

Epidemiological studies combining air quality data such as PM in the vicinity of industrial complexes and health data are scarce. A recent epidemiological study conducted by Bergstra et al. [105] among 89,714 subjects living in the proximity of a large industrial area in the Netherlands have associated industry-related air pollution with the occurrence of chronic diseases (such as cardiovascular and respiratory diseases). The authors found that the exposure to PM₁₀ from industrial sources was significantly associated with a high occurrence of cardiovascular diseases (OR of 1.06; 95% CI of 1.06 to 1.06), and inflammatory conditions (OR of 1.05; 95% CI of 1.00 to 1.09). Another study by Bergstra et al. [106] showed that the exposure of kids (7–13 years) to PM_{2.5} in the proximity of an industrial area (encompassing a coal power plant, terminals for storing coal, a plastic recycling company, an oil refinery, etc.) was associated with decreased lung function. This was concluded after observing a lower percent of predicted peak expiratory flow ($B = -2.8\%$; 95% CI = -5.05% to -0.55%).

The size, shape, and composition of particles emitted in the atmosphere are critical factors that control the extent to which they can penetrate and interact with the human respiratory tract [19]. Atmospheric particles measured in and around industrial complexes are generally enriched with potentially toxic trace elements, generally found in the smallest PM fractions [68,112]. Some of these elements (such as Cu, Zn, Ni, Pb, Mn, Cd), highlighted by Claiborn et al. [113] and Osornio-Vargas et al. [114], have been associated with lung inflammation and damage. They have the capability to generate Reactive Oxygen Species (ROS), initiating cellular oxidative stress, and are considered to play a role in chronic obstructive pulmonary disease (COPD) and asthma [115]. Additionally, the majority of these trace elements, including As, Cd, Co, Cr, Fe, Mn, Mo, Ni, Pb, Rb, Sr, and Zn are slightly influenced by atmospheric processes during transport, and can be considered as conservative tracers [112]. Furthermore, PMs enriched with elements such as Pb, Cd, As, and Hg from both workplace and industrial contamination have been linked with renal tubular and interstitial damage [116]. These elements have the ability to aggravate oxidative stress by binding to glycosylated proteins, enhancing free radical reactions [117–119]. Yang et al. [120] showed that Al, Ca, Fe, K, Mg, Na, and Zn were the most abundant elements in PM collected near iron and steelmaking industries in China and might pose a significant impact on human health. Moreover, the long-term exposure to the emissions of PAHs from industries (aluminum production, coal gasification, tar distillation, etc.) was also associated with an increased risk for bladder cancer [121,122].

Moreover, the socioeconomic impact of industrial pollution from PM affects many facets of daily life, leading to significant healthcare costs, reduced productivity, and a lower quality of life. The healthcare expenses for managing respiratory and cardiovascular diseases can be overwhelming, encompassing hospital stays, more frequent emergency room visits, outpatient care, and medication costs [123]. The impact of industrial pollution on productivity is another critical concern. Air quality directly affects labor force performance; studies indicate that poor air quality correlates with reduced worker efficiency and increased absenteeism. Research has shown that a $10 \mu\text{g}/\text{m}^3$ increase in $\text{PM}_{2.5}$ concentration can lead to a 1% decrease in productivity [124]. This is particularly pronounced in industries that rely heavily on outdoor work, such as agriculture [125]. The decline in quality of life is one of the most intangible yet profound consequences of industrial pollution, contributing to increased stress, anxiety, depression, and other mental health issues [126–128].

To sum up, epidemiological studies have tried to establish correlations between exposure to PM from industrial complexes and a range of carcinogenic and non-carcinogenic health effects. Future research should focus on longitudinal cohort studies and advanced modeling techniques to more accurately estimate exposure levels. Moreover, the integration of a geographic information system (GIS) can enhance the precision of exposure and health outcome mapping. Additionally, studies should increasingly focus on personal exposure by using emerging technologies such as wearable sensors to enable more accurate real-time data collection.

4. Source Apportionment of PM in Industrial Influenced Sites

The identification and quantitative attribution of ambient PM and its components (carbon species, sulfates, nitrates, metal (loid)s, and other species) to their sources is a critical step in supporting the development of air quality management strategies [129]. This apportionment can be determined by different approaches: source-oriented models and receptor-oriented models [130]. Source-oriented models use emission inventories and atmospheric transport models to determine the contributions of the sources, such as the Particulate Matter Source Apportionment Technology (PSAT) in the Community Multiscale Air Quality Model (CMAQ), the Integrated Source Apportionment Method (ISAM) in CMAQ, and the CMAQ decoupled direct method (CMAQ-DDM) [131]. These models utilize comprehensive emission inventories, allowing for a clear understanding of emissions from various sources (e.g., industrial, vehicular). This can help identify specific

contributions and support targeted regulatory measures. However, the accuracy of source-oriented models depends heavily on the quality of the emission inventories. Incomplete or inaccurate data can lead to significant uncertainties in pollution estimates [132].

On the other hand, receptor-oriented models distribute the mass of an atmospheric pollutant at a given site to its sources of emissions by solving a mass balance equation [130]. These models focus on measuring pollutant concentrations at specific sites, providing a direct assessment of air quality and health impacts. This approach can effectively identify the sources contributing to pollution at a particular location. However, while they can show the contributions of different sources to pollution at a specific receptor, these models may not capture the temporal or spatial variations of source-specific molecular markers [133,134].

The selection of a suitable receptor model depends mainly on the degree of knowledge about the sources that is required before applying it. For instance, the Chemical Mass Balance model (CMB) requires chemical fingerprints as input data, in contrast to multivariate models such as Positive Matrix Factorization (PMF), which operate without this requirement [135]. Nevertheless, it is important to have local or regional source profiles for multivariate models in order to correctly assign profiles to the emission sources. Several parameters might change the weight fractions of the chemical species and can influence the source profiles such as the sampling method, the type of fuel and its sulfur content for fuel combustion emissions, and the biofuel categories for biomass burning, as well as the type of process and the final product for industrial sources [136].

4.1. Available Database for Industrial Source Profiles

PM source profiles have been determined worldwide, with particular emphasis on the USA, Europe, and East Asia. Notably, the US EPA initiated the creation of the SPECIATE database in 1988, which subsequently transitioned to an online version in 1993 [137]. This comprehensive database provides speciation profiles, presenting the chemical composition of PM and VOCs emitted from an emission source, and is expressed in weight percentage. The newest version, updated in September 2023, (SPECIATE 5.2) contains 6845 profiles of PM and gas and gathers 3035 unique species [138]. 33% of the PM profiles are dust profiles (mainly road and industrial dust), while 62% are for combustion processes (biomass burning, cooking, industrial and residential combustion, mobile emissions, electric generation, etc.). Source profiles associated with industrial emissions constitute 43% of total PM profiles, including chemical manufacturing, electricity generation, metal and petrochemical industries, etc.

With the aim of filling the gap in the availability of input data for source apportionment in European locations, the European Commission's Joint Research Centre developed the SPECIEUROPE database [139]. This initiative was prompted by the limited availability of localized source profiles in the continent, posing a significant challenge for receptor modeling. The fingerprints provided are either original, composite (combining various subcategories of comparable sources), theoretical (e.g., stoichiometric ratios), or derived (as from CMB outputs). This database contains to date (January 2024) 287 PM and TSP profiles, mainly including profiles for traffic (66), industrial emissions (109), and biomass and other combustion sources (82). The source profiles under the "industrial" category mainly gather profiles from iron and steel industries, cement and ceramic manufacturing plants, power plants, metallurgy, and fertilizer industries.

In 2017, researchers at the Chinese Research Academy of Environmental Sciences (CRAES) introduced the China Source Profile Shared Service (CSPSS 1.0), a novel database containing emission source profiles for particulate matter (PM). This repository encompasses profiles from various sources, including coal-fired boilers, industrial emissions, fugitive dust, vehicular exhaust emissions, biomass burning, and cooking [18].

4.2. Ambiguity of Source Identification in Receptor Models for Industrial Sites

In recent decades, global efforts have been directed towards formulating and assessing action plans and pollution reduction strategies aimed at enhancing air quality worldwide.

Consequently, knowledge about the main emission sources is needed based on established and quantitative data. The application of receptor models in the 1960s, particularly in the United States, Europe, and several developed nations, marked a pivotal moment in this field [140]. Nowadays, this study area is relatively mature regarding the used methods and the ability to adapt new measurement technologies in order to extract the maximum information from the collected data [140]. However, the lack of knowledge of the chemical composition for the emission sources is still a major challenge for source apportionment application, especially in the vicinity of industrial areas. Profile similarity between sources, specifically industrial ones, might limit the sensitivity of the receptor model techniques, causing a collinearity effect [141]. According to Taiwo et al. [21], up to 48% of the PM contributions released by industries are not adequately detected, most likely due to insufficient data, such as low quality analytical data or incorrect analyte sets employed in the model. Most published studies only include OC, EC, ionic components, and elements in their source apportionment model [21].

The literature displays a wide range of reported contributions from industrial sources, with studies presenting values that vary from 1% to 70%, with the majority falling below 10% [21,142,143]. Additionally, in some cases, changes in PM composition during transport might render the source unidentifiable [144]. Several factors might explain the variations of the contribution of the industrial factor to the PM concentrations, such as the distance between the industrial complexes and the sampling site and the meteorological conditions that might favor pollutants dispersion, and the implementation of emission control measures either for PM or some species concentrations in industrial plants. Moreover, the selection of industrial tracers is a critical factor in the receptor models employed [21]. Industrial sources are generally responsible for the emissions of a wide range of elements, depending on the characteristics of the plants. However, the usage of only generic elemental markers in source apportionment studies is difficult due to their lack of specificity, since many elements are co-emitted, but in different proportions from a range of industrial and non-industrial sources [145]. In a recent publication by Hopke et al. [146] including more than 700 PM apportionment exercises from 414 publications, a generic “industry” factor was highly observed and mainly consisted of metallic elements whose origins are not well known. Some sources could be easily identified such as heavy fuel oil combustion since its profile is generally enriched with vanadium, and nickel, as well as significant amount of sulfur [146]. However, it is important to mention that these combustion sources may or may not be directly related to industrial emissions [21]. Other literature references shed light on the overlap between the chemical profiles of crustal dust and anthropogenic origins, as well as between anthropogenic sources (resuspended road dust combined with industrial fingerprints) [147,148]. For instance, elements such as Fe, Zn, and Cu could be emitted from metallurgical industries, particularly sintering factories, and steel plants or from non-exhaust vehicular emissions such as tire abrasion, clutches, and brake pads [143]. According to Gupta et al. [149], the presence of Sr with crustal elements (Fe, Al, Si, nss-K) might suggest the mixing of industrial dust with road dust, whereas the presence of EC in the profile might be attributed to black carbon manufacturing units.

On one hand, an intercomparison of PM₁₀ source apportionment between 33 European research groups was conducted where industrial activities were considered the most difficult sources to be quantified by receptor models, with high variability in the estimated contributions [150]. On the other hand, a few studies have compared two or more receptor modeling approaches for source apportionment in industrial sites. Callén et al. [151] obtained a good agreement in the results from different models: a combined factor of “industrial + road traffic” was observed in the Principal Component Analysis (PCA), Unmix, and PMF, with a contribution varying between 0.6 and 2.9%. Moreover, Viana et al. [152] identified mining and industrial sources in PCA, PMF, and CMB with contributions varying between 32 and 48%. As for Pandolfi et al. [153], CMB was able to provide a contribution from both crustal sources (one natural and one anthropogenic) without observing collinearity between profiles, while PCA and PMF were capable of

identifying an industrial factor leading to differences in the obtained profiles. Finally, Cesari et al. [154] obtained significant differences in the results between PMF and CMB for the harbor-industrial sources, mainly due to the non-compatibility between the source profiles found in the literature and used as input data for CMB and the local specificities of the sources in the region. Taiwo et al. [21] have suggested the usage of multiple receptor modeling techniques (when possible) in order to offer a comprehensive assessment of uncertainties. In addition, authors have suggested conducting receptor modeling at paired sites, comprising one in close proximity to an industrial site and another designated as a background site, enabling a quantitative evaluation of the specific impact attributable to an industrial plant.

In summary, the lack of full chemical profiles for various industrial activities makes the application of source apportionment models highly challenging. Future research should prioritize the development of hybrid models that combine the strengths of both source-oriented and receptor-oriented models approaches. This will help reduce uncertainty in source apportionment, especially in the context of rapidly changing industrial environments.

5. Studies Conducted in the Vicinity of Industrial Areas in East-Mediterranean Middle Eastern (EMME) Countries

The East Mediterranean-Middle East region encompasses the countries of Bahrain, Cyprus, Egypt, Greece, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, Turkey, the United Arab Emirates (UAE), and Yemen. It is located in the “dust belt” and experiences twenty big dust storms every year on average, contributing significantly to global dust emissions (15–20% of the total) [155]. The high-mineral dust concentrations combined with the absence of precipitation have a major effect on ecosystems and human activities, and alter the climate by interacting with solar and terrestrial radiations [156]. On the other hand, because of fast rising urban populations and concentrated industrial sites, anthropogenic activities are recognized as the principal contributors to air pollution and are increasing in the Middle East region [157].

With a population of almost 400 million, this region has a significant human footprint, emitting more than 15% of global SO₂ pollution and 7.5% of greenhouse gases [158–160]. In addition to water scarcity, growing energy demand for industry, traffic, air conditioning, and desalination will also worsen air pollution and greenhouse gas emissions, feeding into environmental and climatic change [26]. It was reported that about half of the air pollutants are attributed to natural sources, with the other half attributed to transportation, energy production, industrial emissions, agricultural operations, waste open burning practices, and household use of unclean fuels for cooking, heating, and lighting [161].

The road transport sector significantly contributes to the air pollution in the region, as highlighted by Waked and Afif [157]. As a consequence, the majority of research has focused on this source of emissions, with comparatively less attention given to industrial emissions. According to the Middle East Economic Statistics, the majority of industries in this region are oil- and gas-related in addition to a significant number of other sectors, such as food processing, cement production, aluminum and plastics, etc. [162]. Furthermore, the Middle East was the world’s greatest oil producer in 2022, accounting for 32.8% of global output. Within all these findings lies the importance of focusing on the industrial emissions typically found in the region: their characteristics, the chemicals released into the atmosphere, and the impacts of these chemicals on human health and the environment.

The East Mediterranean region faces significant challenges in managing air quality due to its distinct climatic features and industrial emissions. The interaction between these factors exacerbates air pollution, particularly through the combination of natural and anthropogenic PM sources. Seasonal winds can carry dust from deserts into urban areas, mixing with industrial emissions and worsening air quality [78]. Dust storms mainly contribute to coarse particles, while industrial activities emit finer PM. When these sources coincide, they create a complex aerosol composition that affects health and the environment in ways that differ from each of the considered sources separately. The combination of

dust and industrial emissions can also lead to chemical changes in the atmosphere. For instance, dust may act as a catalyst for producing secondary pollutants like sulfate and nitrate aerosols, which can be more harmful to health than the original emissions [163]. The combined exposure complicates health risk assessments, as different particles can have different toxicological profiles.

5.1. Search Methodology for Publications Conducted in the EMME Region

For this review, the authors conducted an extensive literature search using various online databases, including Google Scholar, Web of Science, ScienceDirect, Scopus, and PubMed. The detailed research framework is presented in Figure 2. The keywords employed were a combination of the following terms: PM, industrial complexes, chemical characterization, industrial-influenced sites, source apportionment, and health risk evaluation in addition to the names of the different countries in the EMME region.

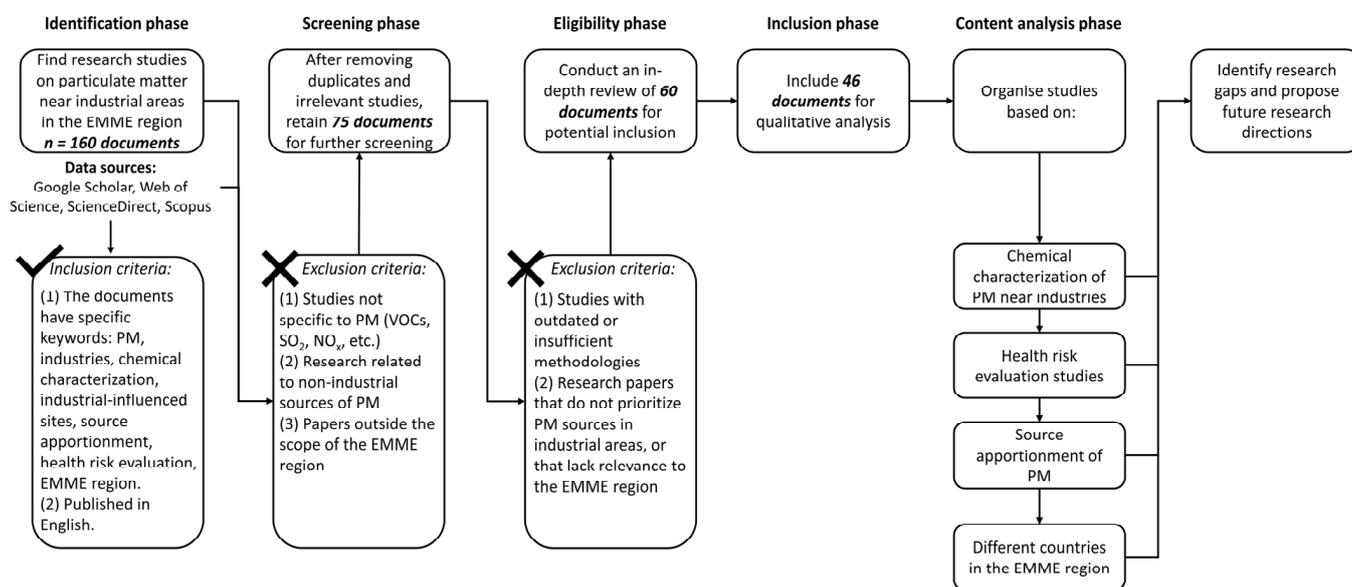


Figure 2. Research framework.

Following the acquisition of articles using the specified keywords, a meticulous filtering process based on the titles and abstracts of the research was employed. Notably, publications including the chemical characterization or source apportionment of compounds in the gaseous phase, the assessments of risk related to the exposure to volatile organic compounds emitted from industrial complexes, and studies in urban, suburban, or rural areas were excluded from consideration (Figure 2).

A total of 46 papers were gathered for this review. Figure 3 presents the yearly number of publications related to PM emissions and its characterization near industrial complexes in the EMME countries. An upward trend in total publications is discernible from 2012 onwards. Nevertheless, this increase is not uniform, and the overall publication count remains relatively low, peaking at seven publications in 2021.

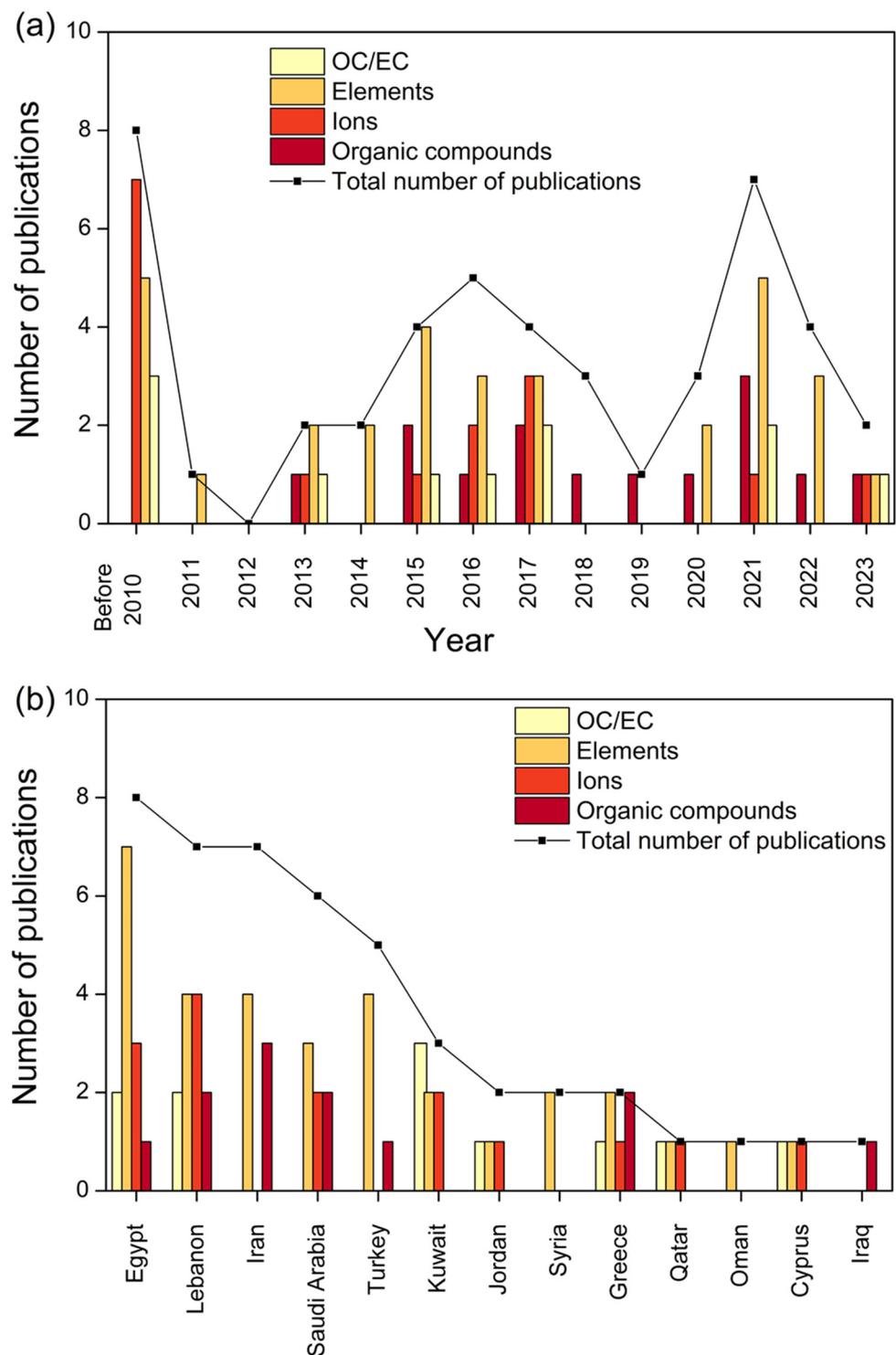


Figure 3. Number of articles published related to PM emissions near industrial complexes in the EMME region (a) throughout the years and (b) per country, and the different characterized species (carbonaceous matter, elements, ions, and organic compounds).

5.2. Overview of the Studies Conducted in the Vicinity of Industrial Areas in the EMME Region

Figure 4 highlights EMME cities where studies in the vicinity of industrial areas were conducted. Egypt, Iran, and Lebanon stood out with the highest number of studies among the 18 countries in the EMME region. It is noteworthy that no studies were undertaken in the United Arab Emirates (UAE), Bahrain, Greece, Israel, Palestine, and Yemen (Figure 4). Additionally, Table 2 offers an overview of the studies conducted in the proximity of

industrial areas within the EMME region. The table outlines essential details, such as the location of the sampling site, the sampling time intervals, the chemical characterization of PM conducted, and the key findings regarding industrial emissions. The table also indicates whether the authors conducted source apportionment modeling for PM or included health risk assessment models.



Figure 4. Geographical representation of EMME countries, pinpointing cities where studies in close proximity of industrial areas were conducted.

5.2.1. Chemical Characterization of PM

The studies have scrutinized diverse chemical components, encompassing organic carbon (OC), elemental carbon (EC), water-soluble ions, elements, and organic compounds. A total of 26 studies focused on the analysis of one family of compounds, with 16 studies examining elements, nine studies examining organic compounds, and one study analyzing ions (Table 2). Furthermore, 15 studies concurrently investigated two or more types of species, including combinations such as ions and elements (four studies); elements and organic compounds (one study); OC, EC, and ions (one study); OC, EC, and elements (one study); OC, EC, ions, and elements (six studies); and OC, EC, ions, elements, and organic compounds (one study). Another study delved into the analysis of total carbon, ions, elements, and organic compounds. The majority of the studies gathered data on either PM_{2.5} or PM₁₀, with a few also collecting data on total suspended particles (five studies). The majority of the studies conducted in the EMME region have specifically focused on elements, with particular emphasis on countries such as Egypt, Oman, Iran, Syria, Saudi Arabia, Lebanon, and Turkey (Table 2).

The PM concentrations in the region are highly variable and depend on the sampling site and its surroundings. Nevertheless, all the studies reporting PM_{2.5} or PM₁₀ concentrations near industrial areas in the region showed values exceeding the WHO annual guideline for PM_{2.5} (5 µg/m³) and PM₁₀ (15 µg/m³) (Table 2). The lowest PM concentrations were observed in Lebanon, Syria, and Cyprus, with PM_{2.5} concentrations ranging between 14 and 34 µg/m³ (Table 2). On the other hand, PM₁₀ concentration levels can reach up to 200 µg/m³ in Saudi Arabia, 320 µg/m³ in megacities like Cairo, and 423 µg/m³ in Iran [164–166]. The PM concentrations in the region are higher than those reported in most European countries, where PM_{2.5} levels in 2022 were below the European Union

annual limit of $25 \mu\text{g}/\text{m}^3$ [167]. However, they are comparable to concentrations reported at industrial sites in China [168,169].

The EMME region is considered to be one of the global hotspots of dust storm activity that has serious effects on air quality, human health, and climate [170]. The major sources that can be found in the region are mainly related to secondary inorganic aerosols and dust followed by other anthropogenic sources such as road traffic, biomass burning and wildfires, and industrial emissions [129]. The studies presented in Table 2 showed that elements such as Pb, Zn, Ni, Cd, Cr, Cu, Mn, and As were mainly emitted from metallurgical industries [171–173], while Ca, Fe, Al, and Si might be tracers of cement production industries [78,174,175]. Industries using oil combustion were characterized by emissions enriched in V, Ni, and Cr [176,177], while petrochemical complexes emit Cu, Pb, Cd, Zn, and Mn, which can be used as tracers of such activities [178,179] (Table 2).

Another type of pollutant originating from industrial emissions is carbonaceous species, which include OC and EC. Fuel-based combustion activities are the primary source of EC, tying them closely to primary emissions, while OC can originate from both primary and secondary sources [180]. Table 3 compiles data on OC, EC, and OC/EC concentration ratios from studies conducted in the vicinity of industrial areas in the EMME region. Abu-Allaban et al. [164,181] reported elevated concentrations of OC and EC in the $\text{PM}_{2.5}$ fraction in Egypt, with levels ranging between 9.4 and $55.6 \mu\text{g}/\text{m}^3$ for OC and 5.8 – $16.1 \mu\text{g}/\text{m}^3$ for EC.

Table 2. Overview of PM-related studies conducted in proximity to industrial areas within the EMME region with a focus on source apportionment (SA) and health risk assessment (HRA) application.

Country/ City Reference	Time Interval	PM _x	PM _x Concentrations	Chemical Characterization	SA Model *	HRA Study	Type of Industries	Main Emissions
Egypt/ Greater Cairo (GC) [164]	February–March and October– November 1999	PM ₁₀	186–265 µg/m ³	OC, EC Ions (NH ₄ ⁺ , NO ₃ ⁻ , SO ₄ ²⁻ , Na ⁺ , Cl ⁻ , K ⁺)	CMB (N/A)	–	Shobra Kheima (heavily industrialized area, downwind of lead smelters)	Pb
		PM _{2.5}	61–216 µg/m ³	Elements (Al, Si, Ca, Fe, Pb, K)			El Maasara (cement plants)	Crustal components (Si, Ca, Fe, and Al)
Egypt/ GC [181]	February–March and October– November 1999 Jun. 2002	PM ₁₀	153–317 µg/m ³	OC, EC Ions (NH ₄ ⁺ , NO ₃ ⁻ , SO ₄ ²⁻ , Cl ⁻)	CMB (N/A)	–	Shobra Kheima (heavily industrialized area, downwind of lead smelters) El Maasara (cement plants)	Pb (fresh emissions from secondary Pb smelters); high concentrations of crustal species (Si, Ca, Fe, and Al), fugitive dust emissions
		PM _{2.5}	61–216 µg/m ³	Elements (Al, Si, Ca, Fe, Pb)				
Egypt/ GC [182]	2001–2002	PM ₁₀	170 µg/m ³	Element (Pb)	–	–	Combustion of mazut and lead smelting	Pb
		PM _{2.5}	85 µg/m ³					
Egypt/ Alexandria [183]	July–August 2010 December 2010–January 2011	Gas + particles	-	Organic compounds (PAHs)	MLR PMF UNMIX (34)	ILCR	Medium and heavy-duty trucks powered by diesel engines Natural gas	–
Egypt/ GC [184]	September and October 2010	PM _{2.5}	12 µg/m ³	Elements (Cd, Cu, Ni, Pb)	–	–	Shobra El Khema	Industrial activity is not the main source of these elements
Egypt/ Giza (part of GC) [171]	2013–2014	PM _{2.5}	103–250 µg/m ³	Ions (NH ₄ ⁺ , NO ₃ ⁻ , SO ₄ ²⁻ , Na ⁺ , Cl ⁻ , K ⁺ , Mg ²⁺ , Ca ²⁺) Elements (Fe, Mn, Al, Zn, Pb, Ni, Cd, Cr, Cu, Co)	–	–	–	Elements such as Zn, Pb, Ni, Cd, Cr, Cu and Co might be emitted from industrial metallurgical processes
Egypt/ Cairo [185]	2014–2015	PM _{2.5}	27 µg/m ³	Elements (Na, Al, Si, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Br, Rb, Sr, Ba, Pb)	–	–	Helwan district (cement plants, iron and food industries, oil and electrical industries)	Al from Aluminum smelting; K from biomass combustion; Zn from metal, bronze, and brass smelters

Table 2. Cont.

Country/ City Reference	Time Interval	PM _x	PM _x Concentrations	Chemical Characterization	SA Model *	HRA Study	Type of Industries	Main Emissions
Egypt/ Cairo [186]	October 2010–May 2011	PM _{2.5}	70 µg/m ³	Elements (S, Cl, K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, Sr, Br, Rb, Pb)	PCA (32)	–	Shobra El Khema	Pb from industries; S from heavy fuel oil combustion
Oman/ Sohar [172]	–	TSP	171–274 µg/m ³	Elements (Cr, Cu, Mn, Ni, Pb, Zn)	PCA (31)	–	Cu industrial processes and reinforcement steel production	Cu and Mn
							Black and galvanized iron pipes production, mechanical industries, and vehicle construction	Cr, Pb, and Zn
							Municipal incineration	Zn and Pb
Jordan/ Zarqa [187,188]	January– December 2007	PM _{2.5}	43 µg/m ³	OC, EC Ions (NO ₃ [−] , SO ₄ ^{2−}) Elements (Si, Al, Ca, Fe)	PMF (50/site)	–	Heavily industrialized area with metal processing industries	EC and SO ₄ ^{2−} from local primary emission from sulfur-rich diesel; EC and Pb from leaded gasoline fuel used in industrial processes
Iran/ Tehran [189]	July 2012–April 2013	PM ₁₀	129 µg/m ³	Elements (Al, Ca, Mn, V, K, Na, Fe, Sc, Zn, Pb, S, Ni, Cd, As, Hg)	–	–	Accumulation of industries in District 16 of Tehran	Cd, Ni
Iran/ Tabriz [190]	September 2012–June 2013	PM ₁₀	85 µg/m ³	Elements (Al, As, Ba, Be, Cd, Co, Cr, Cu, Fe, La, Li, Mn, Mo, Ni, P, Pb, Sb, Se, Sn, Sr, Te, Ti, Tl, Y, Zn, Zr, Pt, Rh, V, Si, and Hg)	PCA (60)	–	Petroleum refinery, small industrial estate	–
Iran/ Isfahan [173]	March 2014–March 2015	PM _{2.5}	–	Elements (Cd, Ni, Cu, As, Pb, Mn, Cr)	PCA (N/A)	–	Iron and steel plants	Pb, Cd, Mn, Ni, Cu, As, Cr

Table 2. Cont.

Country/ City Reference	Time Interval	PM _x	PM _x Concentrations	Chemical Characterization	SA Model *	HRA Study	Type of Industries	Main Emissions
Iran/Ahvaz metropolis [166]	September 2016	PM ₁₀	423 µg/m ³	Organic compounds (PAHs)	PMF (30)	ILCR	Major oil and gas-related industries and steel industry	Nap, Ace, Phe, DiB[a,h]An, InPy
Iran/ Tehran [191]	March 2018–March 2019	PM _{2.5}	37–55 µg/m ³	Heavy metals (Fe, Cu, Pb, Zn, Cd, Mn, Al, and Cr) Organic compounds (PAHs)	UNMIX (36)	ILCR and HQ	Cement and lime production, power plant, aluminum, and asphalt production factories, welding shops	–
Iran/ Karaj City [192]	February 2018–January 2019	PM _{2.5}	38–50 µg/m ³	Organic compounds (PAHs)	PMF (130 for 3 sites)	ILCR	Site under the influence of Alborz Province which is home to 3500 industrial units	Nap, DiB[a,h]An, InPy, B[ghi]Pe
Iran/ Isfahan city [193]	December 2017–September 2018	PM _{2.5}	60 µg/m ³	Organic compounds (PAHs)	PMF (200 for 50 sites)	ILCR	Steel and iron industries, petrochemical plants, oil refineries, cement and brick factories, power plants, and lead and zinc mines	Fla, Chr, Pyr, B[a]P, B[e]P, B[a]An, InPy, B[ghi]Pe for several industrial activities Phe, Fla, B[a]An, Chr, and Pyr from natural gas combustion from power plants
Kuwait/ South site [194]	2004–2005	PM ₁₀ PM _{2.5}	66–93 µg/m ³ 31–38 µg/m ³	OC, EC Ions (NO ₃ ⁻ , SO ₄ ²⁻)	–	–	Refineries, cement factory, fertilizer plant, petrochemical factory, and chemical industries	NO ₃ ⁻ , SO ₄ ²⁻ might be associated with industrial sources
Kuwait/ Kuwait City [195]	February 2004–October 2005	PM ₁₀ PM _{2.5}	130 µg/m ³ 53 µg/m ³	OC, EC Ions (NO ₃ ⁻ , SO ₄ ²⁻) Elements (S, Al, Mg, Fe, Ca, K, Si, Ni, Mn, V, Cu, Zn, Pb, Na, Cl, Ti, Br, Sr)	PMF (117)	–	Petrochemical industries in the countries to the south of Kuwait and along the Arabian Gulf	NO ₃ ⁻ , OC and S

Table 2. Cont.

Country/ City Reference	Time Interval	PM _x	PM _x Concentrations	Chemical Characterization	SA Model *	HRA Study	Type of Industries	Main Emissions
Kuwait/ Ali Sabah Al-Salem [179]	October 2017–October 2019	PM ₁₀	112 µg/m ³	OC, EC Elements (Na, Mg, Al, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Br, Sr, Zr, Pb)	PMF (N/A)	–	Near industrial and petrochemical facilities (Fossil fuel combustion)	Zn and Pb
		PM _{2.5}	42 µg/m ³					
Lebanon/ Chekka [196]	August–October 2008	TSP	–	Ions (NH ₄ ⁺ , NO ₃ [–] , SO ₄ ^{2–} , Na ⁺ , Cl [–] , K ⁺ , Mg ²⁺ , Ca ²⁺ , F [–] , PO ₄ ^{3–}) Elements (Na, Mg, Al, K, Ca, Fe, Ti, V, Cr, Mn, Ni, Cu, Zn, Pb, Cd)	–	–	Cement factories, quarries, phosphate fertilizer industry	Higher NO ₃ [–] concentrations at sites closer to the cement plants
Lebanon/ Selaata [174]	April–June 2008	TSP	–	Ions (NO ₃ [–] , SO ₄ ^{2–} , Cl [–]) Elements (Na, Mg, Al, K, Ca, Fe, Ti, V, Cr, Mn, Ni, Cu, Zn, Pb, Cd)	–	–	Phosphate fertilizer industry Cement plants	P from the factory; Ca from heavy machinery activities and/or rocks grinding in the factory; V, Ni, and Cr from oil combustion
Lebanon/ Zakroun [77]	February–April 2014	PM _{2.5–0.3}	19 µg/m ³	Total carbon Ions (NH ₄ ⁺ , NO ₃ [–] , SO ₄ ^{2–} , Na ⁺ , Cl [–] , K ⁺ , Mg ²⁺ , Ca ²⁺ , F [–] , PO ₄ ^{3–}) Elements (Ag, Al, As, Ba, Cd, Co, Cr, Cu, Fe, La, Mn, Ni, P, Pb, Sb, Se, Sn, Sr, Ti, V, Zn) Organic compounds (PAHs and n-alkanes)	–	–	Cement factories and quarries Phosphate fertilizer industry	Ca ²⁺ , K ⁺ , PO ₄ ^{3–} , and SO ₄ ^{2–} , constituents of the raw materials used in cement plants or fertilizer industries DiB[a,h]An, InPy, and B[a]P emission from scrap tires combustion in cement factories
Lebanon/ Zouk Mikael [197]	January–March and June–July 2015	–	–	Organic compounds (PAHs)	–	–	Power plant running on HFO	–

Table 2. Cont.

Country/ City Reference	Time Interval	PM _x	PM _x Concentrations	Chemical Characterization	SA Model *	HRA Study	Type of Industries	Main Emissions
Lebanon/ Zouk Mikael and Fiaa [78,198,199]	December 2018–October 2019	PM _{2.5}	26–34 µg/m ³	OC, EC Ions (NH ₄ ⁺ , NO ₃ ⁻ , SO ₄ ²⁻ , Na ⁺ , Cl ⁻ , K ⁺ , Mg ²⁺ , Ca ²⁺) Elements (Mn, Mg, Ca, K, Al, Ba, Fe, P, Ti, V, Zn, Cu, Ni, Cr, Pb, Sr, As, Sc, Cd, Co, Rb, Nb, Sn, Sb, La, Ce, Tl, Bi)	PMF (90/site)	ILCR and HQ	Power plant running on HFO at Zouk Mikael	V and Ni from HFO combustion InPy from HFO combustion
				Organic compounds (n-alkanes, hopanes, PAHs, fatty acids, phthalates, dicarboxylic acids, secondary biogenic compounds)			Cement plants and quarries at Fiaa	Ca from the cement plant V and Ni from HFO combustion
Qatar/ Doha [178]	May–December 2015	PM ₁₀	146 µg/m ³	OC, EC Ions (NO ₃ ⁻ , SO ₄ ²⁻) Elements (Ca, Si, S, Fe, Al, Mg, K, Cl, Na, Ti, Sr, Mn, Zn, Ba, V, Br, Cu, Ni, Pb, Cr, Zr, Co, Ce, Sn, Rb, Se, Mo, Ag, Sb, Cd)	PMF (98 per PM size)	–	Fossil fuel burning in petrochemical and industrial metallurgical activities in the area Shipping traffic in the Arabian/Persian Gulf	V and Ni Mn, Zn, Cu, Br, Pb, Na, Cr
		PM _{2.5}	40 µg/m ³					
Syria/ Tartous and Darya [200]	October 2000–October 2001	TSP	171–557 µg/m ³	Elements (Pb, Cu, Zn)	–	–	Tartous: Cement factory, phosphate and coal loading activities into ships	Cu from oil and wood combustion
							Darya: plastic modeling, cosmetics, paint, metal electroplating, lead batteries, recycling and metal melting	Zn from metal smelting and electroplating and batteries recycling Pb from paint
Syria/ Damascus [177]	May 2017–January 2018	PM _{2.5–10}	19 µg/m ³	Elements (Ca, S, Si, Fe, Al, K, Mg, Na, Cl, Pb, Zn, Ti, P, Mn, Cu, Sr, Zr, Br, Ni, V)	PCA (59)	–	Fuel combustion and industrial emissions	Zn, Cu, Br, Pb
		PM _{2.5}	32 µg/m ³				Industrial processes involving oil burning	S, V, Ni

Table 2. Cont.

Country/ City Reference	Time Interval	PM _x	PM _x Concentrations	Chemical Characterization	SA Model *	HRA Study	Type of Industries	Main Emissions
S. Arabia/ Taif [201]	October 2011–June 2012	PM _{2.5}	57 µg/m ³	Elements (Si, S, Cl, K, Ca, Ti, Mn, Fe, Ni, Cu, Zn, Rb, Sr, Pb)	–	–	Industrial district	–
S. Arabia/ Riyadh [202]	September 2011–September 2012	Gas + particles	–	Organic compounds (PAHs)	PMF (56)	–	Oil combustion from energy production	Phe, Fla, Pyr
							Petrochemical processing	Nap and two-rings LMW PAHs
S. Arabia/ Jeddah [203]	February–April 2013	Gas + particles	–	Organic compounds (PAHs)	PMF (N/A)	–	Oil refinery	Fla, Pyr, DiB[a,h]An
S. Arabia/ Rabigh [175]	May–June 2013	PM _{2.5}	37 µg/m ³	Ions (NH ₄ ⁺ , NO ₃ [−] , SO ₄ ^{2−} , Na ⁺ , Cl [−] , K ⁺ , Mg ²⁺ , Ca ²⁺ , C ₂ O ₄ ^{2−}) Elements (Si, S, Ca, Al, Fe, Na, Cl, Mg, K, Ti, Br, Mn, Zn, Sr, V, Lu, Ni, Er, Pb, Cu, Ce, Rb)	PMF (N/A)	–	Industrial dust/Cement	Ca, Fe, Al, Si, Cr
							Fossil fuel (heavy oil) combustion	V, Ni, Pb, Lu, Cu, Zn, NH ₄ ⁺ , SO ₄ ^{2−}
S. Arabia/ Al-Jubail Ras Tanura [204]	May–June 2018 and June–July 2018	PM ₁₀	75 µg/m ³	Elements (Zn, Mg, Na, Al, Si, S, Cl, K, Ca, Fe, Sr, Zr, Ba)	–	–	Steel making industry	Zn
							Aluminum plant	Al
S. Arabia/ Makkah [165]	March 2020–March 2021	PM ₁₀	204 µg/m ³	Ions (NO ₃ [−] , NO ₂ [−] , SO ₄ ^{2−} , Na ⁺ , Cl [−] , Mg ²⁺ , Ca ²⁺ , F [−] , PO ₄ ^{3−} , Br [−])	PCA (N/A)	–	Industrial and construction-demolition emissions	SO ₄ ^{2−} , Mg ²⁺ , Ca ²⁺ , F [−]
Cyprus/Limassol [176]	January 2012–January 2013	PM ₁₀	32 µg/m ³	BC, OC and EC, Ions (nitrate and sulfate), Elements (Na, Mg, Al, Si, S, Cl, K, Ca, Ti, V, Mn, Fe, Ni, Cu, Zn, Se, Br, Sr, Ba, Pb)	PMF (295)	–	The biggest industrial center in Cyprus, ~600 m from the small port, and a few kilometers from the main port of high commercial and passenger traffic flow	Oil combustion: V and Ni
		PM _{2.5}	14 µg/m ³					

Table 2. Cont.

Country/ City Reference	Time Interval	PM _x	PM _x Concentrations	Chemical Characterization	SA Model *	HRA Study	Type of Industries	Main Emissions
Iraq/Basrah [205]	December 2021–February 2022	PM ₁₀	-	Organic compounds (PAHs)	-	LCR	Near seven major petroleum oil fields and refineries	Most abundant PAHs: Chr, Fl, B[b]Fl
Turkey/Kütahya [94]	Summer and winter 2015	PM _{>10.2} , PM _{10.2–4.2} , PM _{4.2–2.1} , PM _{2.1–1.3} , PM _{1.3–0.69} , PM _{<0.69}	42–171 µg/m ³	Organic compounds (PAHs, n-alkanes, carboxylic acids)	-	-	Near thermal power plant	Diagnostic ratios for PAHs and CPI for n-alkanes indicative of coal combustion and biomass burning from heating and power generation
Turkey/Izmir [206]	August 2004 and March–April 2005	TSP	192–200 µg/m ³	Elements (Cd, Cr, Cu, Fe, Mn, Ni and Pb)	PCA (50/site)	-	Petroleum refinery, iron smelters with scrap iron storage and classification sites, steel rolling mills, a natural gas-fired power plant, a very dense transportation activity of scrap iron trucks, ship dismantling area, and busy ports with scrap iron dockyards	Cu, Pb, Cd, Mn from industrial emissions
Turkey/ Bursa [207]	May 2007–April 2008	PM ₁₀ PM _{2.5}	53 µg/m ³ 83 µg/m ³	Elements (Li, Be, V, Cr, Fe, Mn, Co, Ni, Cu, Zn, As, Se, Sr, Cd, Sb, Ba and Pb)	-	-	Textile, automobile, and metal processing industries	Spikes of Sr related to industrial metal process; higher concentrations of Pb, Ni, and Cd due to industrial activities
Turkey/ Konya [208]	2019–2020	PM ₁₀	33–122 µg/m ³	Elements (Pb, Ni, As, Cd)	-	-	Metal industry and galvanizing plants Domestic and imported coal used for industrial activities	Ni As

Table 2. Cont.

Country/ City Reference	Time Interval	PM _x	PM _x Concentrations	Chemical Characterization	SA Model *	HRA Study	Type of Industries	Main Emissions
Turkey/ Ergene Basin [209]	June 2015–May 2016	PM ₁₀	22–23 µg/m ³	Elements (Al, As, Ba, Cd, Cr, Co, Mn, Ni, Pb and Se)	–	CR, HQ	Manufacturing of household appliances, pharmaceuticals, rubber-plastics, textile, carpet, metals, cable, chemicals, hydraulic and agricultural machinery, automotive parts	High CR for Cr
		PM _{2.5}	12–14 µg/m ³					
Thessaloniki/Greece [210]	June 2011–May 2012	PM _{2.5}	38 µg/m ³	OC, EC Ions (NH ₄ ⁺ , NO ₃ [−] , SO ₄ ^{2−} , Na ⁺ , Cl [−] , K ⁺ , Mg ²⁺ , Ca ²⁺) Elements (Pb, Ni, Cu, V, Mn, Cr, Zn, Mg, K, Ti, Fe, Ca, and Al) Organic compounds (PAHs)	–	–	Oil refinery, petrochemical, fertilizer and cement production, non-ferrous, metal smelting, iron and steel manufacturing, metal recovery facilities, electrolytic MnO ₂ production, anodized Al, scrap metal, incineration, tire production and lubricating oil recovery	Flu, Pyr, B[a]A, Chr, B[ghi]Pe from industrial furnaces
Volos/Greece [211]	January 2014–January 2016	PM ₁₀	–	Elements (Pb, Cd, Cr, Mn, Ni, Pb, Fe and Zn) Organic compounds (PAHs)	–	–	Industries of all sectors Large cement production industry	Higher concentrations of As, Fe, Mn, Cr, Ni, Phe, and Pyr when the wind blows from the industrial zone

Naphthalene (Nap), acenaphthylene (Acy), acenaphthene (Ace), fluorene (Flu), anthracene (Anth), phenanthrene (Phe), fluoranthene (Fla), pyrene (Pyr), benz[a]anthracene (B[a]An), chrysene (Chr), benzo[b]fluoranthene (B[b]Fl), benzo[k]fluoranthene (B[k]Fl), benzo[a]pyrene (B[a]P), indeno [1,2,3-c,d]pyrene (InPy), dibenz[a,h]anthracene (DiB[a,h]An), and benzo[ghi]perylene (B[ghi]Pe), N/A: not available. * (# of samples included in the model).

The average concentrations of both OC and EC were observed to be in the range of 1.79–4.6 $\mu\text{g}/\text{m}^3$ and 0.5–2.94 $\mu\text{g}/\text{m}^3$, respectively, as reported for different sites in the EMME region, including Lebanon, Kuwait, and Qatar. The OC/EC concentration ratio serves as a valuable diagnostic metric, offering insights into the sources within $\text{PM}_{2.5}$. For diesel vehicles, the OC/EC ratios typically fall between 0.3 and 1, while for gasoline-operated vehicles, the range is between 1.4 and 5, as reported by Salameh et al. [212]. Higher ratios were linked to sources such as biomass burning (4.1–14.5), open waste burning (7.5), and cooking emissions (33–82) [213,214]. According to Riffault et al. [19], the OC/EC ratio in the vicinity of industrial sites is highly variable and is dependent on the type of industrial activity near the sampling site. Additionally, reported ratios in sites near industrial activities fall in the range of other sources which makes the identification of sources of carbonaceous matter more challenging. The values reported in Table 3 varied between 0.8 and 6.45. Such values are in the range of those found in the literature for urban sites and might be attributed to a mix of sources including non-industrial ones.

Table 3. OC and EC concentrations (expressed in $\mu\text{g}/\text{m}^3$), as well as OC/EC concentration ratios for studies conducted in the vicinity of industrial areas in the EMME region.

City (Country)	Site	PM_x	OC ($\mu\text{g}/\text{m}^3$)	EC ($\mu\text{g}/\text{m}^3$)	OC/EC	References
Cairo (Egypt)	Industrial/Residential (Shobra Kheima—Winter 1999)	$\text{PM}_{2.5}$	32.7	12.4	2.64	[164]
		PM_{10}	42.2	10.0	4.22	
Cairo (Egypt)	Industrial/Residential (El Maasara—Winter 1999)	$\text{PM}_{2.5}$	9.4	7.6	1.24	[164]
		PM_{10}	22.4	7.5	2.99	
Cairo (Egypt)	Industrial/Residential (Shobra Kheima—Fall 1999)	$\text{PM}_{2.5}$	55.6	16.1	3.45	[181]
		PM_{10}	86.5	13.4	6.45	
Cairo (Egypt)	Industrial/Residential (El Maasara—Fall 1999)	$\text{PM}_{2.5}$	37.2	6.7	5.55	[181]
		PM_{10}	68.7	8.3	8.28	
Cairo (Egypt)	Industrial/Residential (Shobra Kheima—Summer 2002)	$\text{PM}_{2.5}$	22.2	7.4	3.00	[181]
		PM_{10}	30.2	8.7	3.47	
Cairo (Egypt)	Industrial/Residential (El Maasara—Summer 2002)	$\text{PM}_{2.5}$	18.2	5.8	3.14	[181]
		PM_{10}	28.1	5.8	4.84	
Kuwait (Southern site)	Urban/industrial (February. 2004—October. 2005)	$\text{PM}_{2.5}$	3.7	2.3	1.61	[194]
Kuwait (Ali Sabah Al-Salem)	Industrial/Residential (October 2017—October 2019)	$\text{PM}_{2.5}$	3.22	2.94	1.09	[179]
Lebanon (Zouk Mikael)	Urban/industrial (December 2018—October 2019)	$\text{PM}_{2.5}$	4.6	1.3	4.0	[215]
Lebanon (Fiaa)	Urban/industrial (December 2018—October 2019)	$\text{PM}_{2.5}$	3.0	0.5	7.3	[215]
Qatar (Doha)	Urban/industrial (May—December 2015)	$\text{PM}_{2.5}$	1.79	2.63	0.76	[178]
		PM_{10}	5.18	0.57	2.7	

For instance, in Lebanon, the OC/EC concentration ratio value of 4 at the Zouk site aligned with gasoline vehicle emissions, while a distinct pattern was noted at the Fiaa site (value of 7.3), consistent with biomass burning and open waste burning [78] (Table 3). As for Brown et al. [194], the low OC/EC observed ratio of 1.6 was mainly explained as due to the lack of biogenic sources in Kuwait and the influence of oil production, petroleum refining, and chemical production near the sampling site.

PAHs have been the subject of nine studies in the EMME region, specifically centered on countries like Egypt, Iran, Lebanon, Saudi Arabia, Iraq, and Turkey (Table 2). According to these studies, oil- and gas-related industries emit mainly naphthalene (Nap), acenaphthylene (Acy), phenanthrene (Phe), fluoranthene (Fla), pyrene (Pyr), dibenz[a,h]anthracene (DiB[a,h]An), indeno [1,2,3-c,d]pyrene (InPy) [202,203], while natural gas combustion power plants emit Phe, Fla, benzo[a]anthracene (B[a]An), Pyr, and chrysene (Chr) [193]. Additionally, high levels of DiB[a,h]An, InPy, and benzo[a]pyrene (B[a]P) were attributed to scrap tires combustion from cement factories [77] and InPy to HFO combustion from power plants [198]. Moreover, the emissions of PAHs from industrial sources have a substantial impact on air quality in the EMME region [166,183,192,193,205].

PAHs diagnostic ratios have been used to identify the emission sources and the type of fuel used in the combustion processes [81,216]. The essential premise of this methodology is that the specific ratios remain constant between the emission source and the measurement site. This is especially true for isomers with similar photochemical properties, which are considered to be affected similarly by the various reactions occurring in the atmosphere. Few studies have used this approach to qualitatively identify the sources of PAHs in the EMME region. A brief summary of the most used ratios in the literature and their values according to the different emission sources are presented in Table 4. The calculated diagnostic ratios of Fla/(Fla + Pyr), Phe/(Phe + anthracene (Anth)), B[a]An/(B[a]An + Chr), Chr/(B[a]P + Chr), and InPy/(InPy + benzo[g,h,i]perylene (B[ghi]Pe)) in these studies showed that the dominant sources were mainly related to urban activities e.g., vehicular emissions, fuel combustion emissions, and wood combustion. However, some ratios were attributed to industrial emissions. Khedidji et al. [217] have attributed the Fla/(Fla + Pyr) ratio's value of 0.26 to industrial emissions while Najmeddin and Keshavarzi [166] has ascribed an InPy/B[ghi]Pe ratio's value of 0.25 to heavy fuel oil combustion from the power plant. Moreover, a value of 0.69 for the ratio Chr/(B[a]P + Chr) was attributed to industries, fertilizer production, and heavy fuel in the energy sector [77]. Fadel et al. [198] have defined a characteristic ratio of InPy/(InPy + B[ghi]Pe) in the range of 0.8–1.0 for heavy fuel oil combustion from the biggest power plant in Lebanon.

Other than the PAHs diagnostic ratios, the assessment of the origins of organic species could be evaluated by the carbon preference index (CPI) for alkanes. CPI is defined as the sum of odd carbon number n-alkanes to the sum of even carbon numbers [218]. This parameter is used to evaluate biogenic and anthropogenic contributions to organic aerosols. For instance, biogenic sources emit odd carbon number alkanes in greater concentrations than even carbon number alkanes, and therefore have an overall CPI higher than 6. In contrast, petrogenic emissions exhibit no carbon preference and have a value close to 1, while a value between 2 and 5 indicates biomass burning [198,219]. In the context of industrial processes, n-alkanes typically exhibit a CPI very close to 1 at sites near industrial facilities or those influenced by industrial activities [220,221]. An elevation in this value suggests a stronger influence of biogenic emissions at the sampling site. Hence, this parameter can effectively function as a proxy for assessing the relative contributions of industrial activities and other sources to the overall PM_{2.5} levels at a specific location [220]. In Turkey, the CPI values ranged between 0.68 and 1.14, indicating a significant presence of n-alkanes originating from fossil fuel emissions rather than plant wax [94]. In Lebanon, a similar pattern emerged, with a CPI close to 1, indicating the contribution of a petrogenic source [198].

Table 4. Ratios of PAHs found in studies conducted in the MENA and EMME region in addition to other studies found in the literature.

	Fla/(Fla + Pyr)	Phe/(Phe + Anth)	B[a]An/(B[a]An + Chr)	Chr/(B[a]P + Chr)	InPy/(InPy + B[ghi]Pe)	References
Studies conducted in the MENA and EMME region	0.43–0.51 gasoline car emissions	0.81–0.91 lubricant oils and fossil fuels combustion	0.25–0.34 crude oils		0.24–0.33 vehicular emissions	[222]
	0.48 automobile emissions	0.81–0.86 lubricant oils and fossil fuels combustion			0.44 vehicular emissions	[223]
	0.26 industrial emissions				0.25–0.49 diesel emissions	[217]
	0.32–0.58 gasoline and diesel emissions	0.91–0.66 combustion processes	0.17–0.43 gasoline and diesel emissions		0.22–0.41 gasoline and diesel emissions	[193]
					InPy/B[ghi]Pe of 0.25 mazut combustion in the power plant	[166]
	0.4–0.5 fuel combustion		0.36–0.37 gasoline emissions (road traffic)		0.8–1 HFO combustion from a power plant	[198]
				0.69 industries, fertilizer production, heavy fuel in the energy sector	0.62 wood burning	[77]
	0.2–0.58 diesel combustion	0.7–0.8 unburned fuels				[202]
		0.16–0.37 gasoline and diesel emissions	0.63–0.85 light duty vehicle emissions and coal combustion	0.3–0.49 mixed contribution of diesel vehicle emissions, industrial furnaces and road dust	[94]	

Table 4. Cont.

	Fla/(Fla + Pyr)	Phe/(Phe + Anth)	B[a]An/(B[a]An + Chr)	Chr/(B[a]P + Chr)	InPy/(InPy + B[ghi]Pe)	References
Other studies in the literature	<p><0.2 petrogenic source ^a</p> <p>0.4–0.5 fossil fuel combustion ^a</p> <p>>0.5 wood and coal combustion ^{a,i}</p> <p>0.24 diesel generators ^b</p> <p>0.47–0.56 cooking emissions ^b</p>	<p>>0.9 petroleum sources ^c</p> <p><0.9 pyrolytic origins ^c</p>	<p>>0.35 vehicular emissions ^d</p> <p><0.2 unburned crude oil and petroleum products ^d</p> <p>0.2–0.35 coal combustion ^{d,i}</p> <p>0.41 diesel generators ^b</p> <p>0.43–0.46 cooking emissions ^b</p>	<p>0.67 urban environment ^e</p> <p>0.51 gasoline emissions ^f</p> <p>0.27 diesel emissions ^f</p>	<p>0.82 oil burning from residential heating ^g</p> <p>0.9–0.96 cement plants ^g</p> <p>0.96 diesel emissions from taxis and buses ^g</p> <p>0.2–0.5 gasoline source ^h</p> <p>0.35–0.7 diesel source ^h</p> <p>>0.5 wood and coal combustion ^h</p> <p>0.18 diesel generator ^b</p> <p>0.45 and 0.56 cooking emissions ^b</p>	<p>^a [81]; ^b [224]; ^c [225]; ^d [216]; ^e [226]; ^f [227]; ^g [228]; ^h [19]; ⁱ [229]</p>

Water-soluble ions are not considered to be specific industrial tracers. However, they could indicate the influence of an industrial source when combined with other characterization data. Some studies have found high levels of PO_4^{3-} near fertilizer industries while high levels of Ca^{2+} , K^+ , and SO_4^{2-} could be ascribed to cement plants [77,196].

5.2.2. Health Risk Evaluation

Health risk assessment studies aim to estimate the nature and likelihood of adverse health effects in humans exposed to chemicals in contaminated environments [230,231]. Several studies in the EMME region have estimated the hazard quotient (HQ) or non-carcinogenic risk as well as the incremental lifetime cancer risk (ILCR), mainly for PAHs and elements (Table 2).

Khairy and Lohmann [183] have found that the atmospheric environment in Alexandria, Egypt, is heavily contaminated with PAHs with concentrations in both particulate and gas phases varying between 170 and 1770 ng/m^3 . The ILCR values calculated for this site for dermal contact (6.48×10^{-3} – 4.41×10^{-2}), ingestion (1.31×10^{-5} – 8.92×10^{-5}), and inhalation (1.08×10^{-6} – 5.88×10^{-6}) greatly exceeded the USEPA threshold limit of 10^{-6} . The latter values for inhalation were lower than the one found in Basrah City, Iraq, where the lifetime cancer risk was 8.5×10^{-5} but the average concentration of PAHs was 7.9 ng/m^3 [192]. These differences might be attributed to the different calculation methods used to estimate the inhalation cancer risk for PAHs. As for Iran, the assessment of health risks from PAH exposure at various sites has revealed a considerable carcinogenic threat with ILCR values varying between 8.5×10^{-5} and 2.6×10^{-4} [166,191,193], emphasizing the critical need for implementing strategies to mitigate the levels of these pollutants in the country's ambient air. In Lebanon, a comparable situation emerged, with cancer risk values at two locations, Zouk Mikael (1.4×10^{-5}) and Fiaa (3.7×10^{-6}), surpassing the threshold limit of 10^{-6} for lifetime cancer risk [199].

As for elements, only three studies have reported the hazard quotient and the incremental lifetime cancer risk (Table 2). For the three studies, the reported hazard quotient values for non-carcinogenic risk were lower than the threshold limit of 1 (varying between 7×10^{-7} and 0.4) [191,199,209]. On the other hand, lifetime cancer risk values exceeded the threshold limit at the different sites with maximum values in the 10^{-3} order of magnitude. The major contributors to the cancer risk values were mainly Ni, Cr, Co, and As.

5.2.3. Source Apportionment of PM

According to Table 2, PMF, PCA, and CMB emerged as the most commonly utilized methods in the EMME region for identifying PM sources contributions, and were featured in 13, seven, and two studies, respectively. Among the different studies, seven have utilized the PCA statistical technique to identify the principal sources of elements (Table 2). However, this method is mainly qualitative and does not give any quantitative data regarding the sources' contributions to PM concentrations. On the other hand, the significant usage of the PMF method for source apportionment aligns with the global trend, evidenced by a remarkable 546% increase in worldwide studies employing PMF between 2010–2020 compared to the previous decade [147]. This model is simple to use and does not require prior knowledge of sources profiles, unlike CMB where source profiles are input data for the model.

Regarding PCA studies, Oman's sources of elements encompassed steel production, black and galvanized iron pipes production, mechanical industries, vehicle construction, and municipal incineration [172]. PCA analysis revealed various potential sources of elements in Iran, including fossil fuel combustion, abrasion of vehicle tires, industrial activities such as iron and steel industries, and dust storms [173].

On the other hand, PAHs were used as input data for PMF in six studies. Azimi-Yancheshmeh et al. [192] reported that the primary contributors to PAHs in Karaj, Iran, were diesel and gasoline engine emissions, constituting 37.4% and 31.1%, respectively. Following closely were natural gas and biomass burning at 14.8%, industrial emissions at

10.1%, and petrogenic sources at 6.6%. Pollution from local industries, including gas and oil refineries, welding workshops, metallurgy, petrochemical, cement, and iron and steel manufacturing, is transported across Karaj City, Iran by winds from the northwest and southeast. In the source apportionment study conducted in Jeddah, Saudi Arabia, using PMF, industrial sources, particularly the oil refinery, contributed to 33% of the measured PAH species [203]. The PMF model projected that oil combustion emissions played a predominant role in the PAH concentrations in Riyadh, Saudi Arabia, comprising an average of 96%. This is likely a result of the widespread utilization of oil fuels in various energy production sectors, including power plants and industries.

Four PMF studies have concentrated on OC, EC, ions, and elements as input, specifically in Jordan, Kuwait, Qatar, and Cyprus (Table 2). In Kuwait, the PMF model identified that local sources, including oil combustion, petrochemical industrial sources, and transportation emissions, played significant roles in the observed fine PM. Collectively, these sources contributed to 44% of ambient PM_{2.5} [195]. In Qatar, besides local traffic, significant sources included heavy oil combustion and secondary aerosols, closely associated with regional emissions from shipping vessels and the petrochemical industry in the Gulf region [178]. In Cyprus, a total of seven sources were identified, including regional sulfur, traffic emissions, biomass, re-suspended soil, oil combustion from power plants, road dust, and sea salt [176]. Finally, Fadel et al. [78] have gathered carbonaceous, inorganic, and organic compounds in order to have the most extensive database for source apportionment in industrial cities in the EMME by PMF. HFO combustion from power plants contributed to 13% of PM_{2.5} at the Zouk Mikael site while in the Fiaa site, industrial emissions including HFO combustion and cement production source contribute to 8.2%.

A limited number of studies (two in Egypt) have employed the CMB receptor modeling approach for source apportionment, utilizing OC, EC, ions, and elements as input [164,181]. They have added into their model several chemical profiles found in the literature for industrial sources (cement plant, copper foundry, heavy fuel oil, lead smelter). They have found a considerable contribution of cement plant emissions to PM concentrations at the El Maasara site (4.7–24%), and of lead smelters (4–20%) and copper smelters (2–5.2%) in Shobra Kheima. The results of CMB should always be considered with caution when the chemical profiles of the sources used are not those of the local facility.

It is worth noting that most of these source apportionment studies have used chemical source profiles from the SPECIATE and the SPECIEUROPE databases due to the lack of local profiles. The latter might differ from the literature profiles because of the differences in the process conditions and the abatement techniques (baghouse filters, electrostatic precipitator, etc.), and the composition of the raw materials. Even though it is not expected for the major components to differ, the chemical composition as well as the ratios among different species might slightly change, which can highly influence the result models, such as CMB. This is why it is essential to use the local database from the region.

6. Recommendations, Future Directions, and Conclusions

This review presented the current knowledge regarding particulate matter emitted by industrial activities. It included the physico-chemical characterization of these particles and their health effects, and the health risk evaluation for the population living near different types of industrial complexes. Recommendations and future directions should concentrate on three key areas: data collection, methodological enhancements, and policies and regulatory measures.

6.1. Data Collection

As presented above, the identification of industrial sources via receptor modeling is still challenging and can lead to high uncertainties in the obtained source contributions to the total PM concentrations. Hence, more efforts should be put in place to reduce the ambiguity between source profiles. Increasing the number of samples included in the receptor models is important to have more robust results leading to better profile segre-

gation. The European guidelines emphasize that the recommended number of samples to be used in source apportionment should exceed 100 and that this number should be at least three times greater than the number of variables [130]. This implies the generation of longer time series data or higher sampling frequency, enabling more robust comparisons, especially seasonal ones. Most of the studies conducted in the EMME region in the vicinity of industrial complexes relied on short-term sampling campaigns. Consequently, interpreting them required caution, as seasonal emissions, climate variations, and even short-term weather events (e.g., dust events that are frequent in the region) can influence PM concentrations and source apportionment results. Hence, there is a need for additional studies incorporating longer time series in the region to effectively pinpoint sources and implement suitable mitigation measures for managing air pollution. Moreover, to enhance the reliability of future studies, standardizing data collection is essential in order to improve comparability of results and enable more effective public health interventions. Regional collaborations for data sharing and knowledge transfer are important for strengthening air quality monitoring and management.

6.2. Methodological Enhancements

It is crucial to characterize the different components of PM to accurately identify and quantify the sources of air pollution. Studies that allocate sources based solely on a specific chemical component of PM (e.g., elements, or PAHs or other components) yield different results compared to those utilizing models based on a broader spectrum of components (e.g., OC + EC + elements + ions). Moreover, performing PMF analysis with only organic species neglects important sources that largely contribute to PM mass (e.g., secondary sulfate, secondary nitrate, sea salt, and crustal dust). On the other hand, performing PMF analysis without organic species showed not only the over- and under-estimation of the contribution of some sources, but also the negligence of some other ones or a combination of several sources in one profile. Therefore, to achieve more accurate source apportionment, it is necessary to include species from the carbonaceous fraction, major and trace elements, ions, and organic compounds. To date, among the 18 countries in the EMME region, only one study in the vicinity of an industrial area has reported a full chemical speciation of PM [78,198,199]. Moreover, the latter studies have reported source apportionment, including simultaneously organic and inorganic species in PMF, to identify PM_{2.5} sources and their contributions. To ensure more accurate findings and enable the implementation of effective air pollution control measures, it is imperative for future studies in the region to characterize a diverse range of PM components and include them in the receptor model. It is important to note that certain chemical components can originate from multiple sources (e.g., elements such as Cu discussed in Section 2.2). Additionally, the selection of source markers for receptor modeling should be substantiated and justified by the specific source profiles within the area of interest.

Moreover, the development of local source profiles of particles emitted from industries with a full chemical speciation including organic compounds might reveal either some interesting tracers of industrial emissions or help distinguish between sources by reducing collinearity. These source profiles are important input data for CMB models, but are also crucial in order to assign ambiguous profiles to the right sources in non-CMB type modeling techniques such as PMF.

The usage of multiple receptor modeling techniques can offer a comprehensive assessment of uncertainties. In addition, the usage of the “Lenschow” approach might be important for the evaluation of the impact attributable to an industrial plant. The latter is a simple technique based on conducting receptor modeling at paired sites (industrial and background site for example) and has been widely used to discriminate the local and non-local increments. Additionally, the development of emission inventories for specific chemical components, especially in less developed countries, is essential in order to increase confidence in attributing sources to factors identified through receptor models. It is also im-

portant to continuously improve emission inventories through verification, and utilization of both source-oriented and receptor-oriented source apportionment methods [232].

6.3. Policies and Regulatory Measures

This review compiled the current knowledge about the properties of particulate matter (PM) in the vicinity of industrial areas. The physico-chemical characteristics of particles emitted by industries are highly variable and dependent on the type of industrial activity, leading to different health effects such as higher cancer rates, cardiovascular and respiratory diseases, and inflammatory pathologies. This work has also emphasized the need to better understand and evaluate the influence of industrial activities on particulate pollution on a global scale and more specifically in the EMME region. Despite significant progress in monitoring and modeling air quality, gaps remain in our knowledge, particularly regarding the accurate contribution of different industrial sectors to PM levels, the lack of data in the vicinity of large pollutant emitters, and the complex interactions between various pollutants. For this reason, regional cooperation should be strengthened to support targeted studies assessing the seasonal and long-term impacts of industrial emissions in the EMME region. This effort should prioritize the development of localized emission inventories and the development and improvement of local expertise in air quality management.

Moreover, there is an urgent need for robust regulatory frameworks and effective policy measures to mitigate particulate pollution. Aligning local regulations with international best practices, such as those established by the United States or the European Union, is crucial for ensuring that local policies not only address local needs but also conform to international standards. This will also help in achieving the Sustainable Development goals (SDGs) published by the United Nations in 2015. Additionally, it is essential to incorporate mechanisms for the continuous evaluation and adaptation of these frameworks in response to emerging environmental challenges and public health data. This adaptive approach will facilitate effective strategies for improving air quality and protecting public health. This is reachable through collaboration between the public sector, including regulators, the private sector, including industries, and the scientific community, in addition to public awareness and community engagement regarding the matter.

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