

1 SOURCE APPORTIONMENT OF OXIDATIVE POTENTIAL – WHAT WE KNOW SO FAR

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9 *In numerous epidemiological studies, exposure to particulate matter (PM)*
10 *has been associated with negative health outcomes. It has been established*
11 *so far that the detrimental health effects of particles cannot be explained by*
12 *a single parameter, such as particle mass, as the complexity of chemical*
13 *composition and reactivity of particles are not always represented by the*
14 *mass loadings. The oxidative potential (OP) of aerosol particles represents a*
15 *promising indicator of their potential toxicity. To develop strategies and*
16 *regulations at improving the air quality, an increasing number of studies are*
17 *focused on the application of source apportionment (SA) of PM., while a*
18 *limited number of SA investigations have been applied to OP. In this review*
19 *previous research of SA of atmospheric PM oxidative potential and*
20 *proposed guidelines for future studies are summarized. Most of the research*
21 *studies were carried out in an urban area and focused on PM_{2.5}, while few*
22 *studies examined other PM fractions. It was noted that the three dominant*
23 *contributors to OP were biomass burning (9-97%), secondary aerosols (6-*
24 *67%) and traffic/vehicles (16-88%). The presence of other factors that*
25 *contributed to the increase of OP to a lesser extent depended on the location*
26 *and season. Further, a considerable discrepancy in the contribution of*
27 *various OP vs. PM sources was discovered using SA models. Because of*
28 *this, the use of SA is not equivalent when considering the mass of PM and its*
29 *toxicity.*

30 Key words: *Oxidative potential, Source apportionment, toxicity*

31 1. Introduction

32 The fast changes in pollutant emissions brought on by comprehensive human activity and rapid
33 industry development make air quality one of the main issues in the urban environment. The effects of
34 air pollution on visibility, human health, and global climate change have generated considerable public
35 concern [1, 2]. As a result, quantifying different pollutants in the air has become crucial for authorities
36 to analyze air quality and enact regulations that will help reduce pollution. Although most cities
37 worldwide have policies to control certain pollutants, in urban environments, severe haze episodes still
38 occur primarily during the winter heating season. Also, natural fires that occur during the summer

39 period, when they are difficult to control due to unfavorable weather conditions, also greatly impact
40 air pollution. Numerous research has suggested that particulate matter (PM) is one of the most
41 important pollutant influencing air quality and affecting the greatest number of people. Hence, it is
42 essential to have accurate PM monitoring to create services to lower the amount of pollutants that
43 people would be inhale.

44 The complexity of PM comes from various factors; the varying chemical composition, size of
45 particles, meteorological conditions, emission sources, a great number of transformation reactions,
46 aging in the atmosphere, different measurement and detection techniques. PM mass concentration has
47 been employed as an exposure indicator; however, it may underestimate PM's total impact since it
48 neglects the sizes, composition, toxicological effects, and interactions of its components. Furthermore,
49 a single metric, such as particle mass concentration, cannot fully explain the negative health impacts
50 of particles, and as a consequence, epidemiological study results are fraught with ambiguity. Major
51 chemical components (i.e., mass contributors) may have low or extremely low toxicological activity,
52 causing modest or no detrimental impacts on health, while trace chemical components may have
53 significant toxicological activity. In this regard, PM mass concentration is an inadequate measure for
54 describing the mechanisms through which PM exposure might affect human health. This constraint
55 can be eliminated by determining whether or not there is a connection between PM toxicity and the
56 particular physical and chemical features of PM. In recent years, the PM composition has been the
57 subject of numerous researches. Several PM components have been recognized as crucial in
58 determining its possible health and environmental impacts.

59 Although there are several theories on how short-term or long-term exposure to particles can
60 affect human health, one of the leading theories suggests that the detrimental effect of PM can be
61 attributed to its oxidative or oxidant-generating properties. According to current studies, many
62 negative health impacts are induced by oxidative stress in biological systems produced by PM
63 accumulation in the lungs. Oxidative stress is the imbalance that results from increased radical
64 generation and a decreased capacity for the body to deal with excess radicals or repair the damage
65 caused by radicals [3]. The oxidative stress paradigm is the name given to this developing theory,
66 which states that oxidative stress might occur as a result of two different mechanisms. The first
67 mechanism is associated with the intrinsic oxidation-reduction processes caused by the redox-active
68 compounds contained in PM. These reactions are caused by exogenous reactive oxygen species
69 (ROS). ROS is the collective term for chemically reactive oxygen radicals, such as superoxide ($O_2^{\cdot-}$),
70 hydroxyl ($\cdot OH$), peroxy (RO_2^{\cdot}), and alkoxy ($RO\cdot$), as well as oxygen-derived species, such as
71 hypochlorous acid (HOCl), ozone (O_3), singlet oxygen (1O_2), and hydrogen peroxide (H_2O_2), all of
72 which are oxidizing agents [4]. The second mechanism is the biological reaction to inhaled PM or cell-
73 mediated oxidant-producing capacity. Because of this, a thorough investigation of how airborne
74 particulate matter (PM) affects human health is required.

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76 **2. Reactive oxygen species**

77 Atmospheric ROS can be introduced into the body by inhaling particles that already have ROS
78 attached to them (particle-bound ROS). ROS can be generated through various in vivo reactions
79 catalyzed by specific components present in the particles, defined as oxidative potential (OP) [5, 6].
80 Since the direct measurement of ROS in the air is a complex process, in order to assess the toxicity of

81 particles, the determination of their oxidative potential is increasingly being used. OP is defined as a
82 measure of the ability of particles to oxidize certain molecules, resulting in the formation of ROS [7].
83 Thus, oxidative stress is a key PM toxicity mechanism, and measuring PM oxidative potential might
84 help elucidate downstream pathways. However, monitoring the ROS parameter in the environment
85 may be challenging due to the complex measuring methods involved in biological systems. Also, ROS
86 may be found in the gas phase as well as the particulate phase. Further, there are two types of ROS,
87 short- and long-lived ROS. The former has a half-life of only a few minutes, while the latter can be
88 found in the air for several hours to days [8].

89 In current research, the measurement of OP is performed using various cell-free tests (acellular
90 assays), as well as *in vitro* and *in vivo* tests. Consumption of a different chemical (often antioxidants)
91 or direct detection of ROS production from PM extracts constitutes the basis of cell-free assays.
92 Acellular assays have limited physiological validity, as they are performed without the actual
93 interaction that occurs between the cell and the particles. On the other hand, these assays are easier to
94 use than cell trials and allow relatively fast data reading. They are helpful for a rapid initial hazard
95 screening and require less controlled environments. The advantage of these tests in relation to *in vitro*
96 measurements is reflected mostly in the lower cost of reagents required for analysis, as well as the
97 shorter time needed for the application of the assay.

98 Both *in vitro* and *in vivo* methodological approaches aim to investigate the biochemical and
99 molecular mechanisms of toxic particles. In addition, these tests provide insight into the specific
100 negative effects that particles can cause in humans. *In vitro* methods are based on cultured cells that
101 can be immobilized or freshly collected. Lung cells are most commonly used to analyze ambient
102 particle toxicity [9-11]. These measurements can detect specific changes that occur on the surface or
103 inside cells, which helps to better understand the mechanisms of particle toxicity. The advantages of
104 such tests are reflected in the relatively affordable cost of cell cultures required for testing and
105 measurement speed. However, the main limitation of *in vitro* research is the use of isolated cells,
106 which excludes interaction with neighbouring cells and intercellular signalling, which is necessary for
107 the homeostasis of tissues and organs [12]. *In vivo* methods are applied to living organisms (mice, rats
108 and hamsters) and give the most reliable results in studying particle toxicity. The two main approaches
109 are intratracheal inhalation and intratracheal instillation [13]. Applying the inhalation method requires
110 the possession of expensive chambers in which the animals are exposed to certain particles. In
111 contrast, the instillation method requires directly introducing particles into the trachea. Since the
112 mentioned tests are performed on living organisms, they enable the most relevant results [14].

113 OP cell-free assays are diverse and include dithiothreitol (DTT) assay, ascorbic acid (AA)
114 assay, BPEA nitroxide assay, glutathione (GSH) and dichlorofluorescein (DCFH) assays, p-
115 hydroxyphenylacetic acid (POHPAA) and electron spin resonance (ESR). DTT, GSH and AA assays
116 measure the depletion rate of chemical proxies for cellular reductants (DTT) or antioxidants (AA),
117 which is proportional to the generation rate of ROS, while the ESR measures the generation of ROS
118 via electron spin resonance. On the contrary, particle-bound ROS measurements, such as the DCFH
119 assay and BPEAnit, use fluorescent-based techniques to measure concentrations of specific ROS,
120 usually the hydroxyl radical or hydrogen peroxide in PM samples. These methods usually reveal a
121 different response to the chemical constituents of PM, and they differ greatly in sensitivity and
122 application. Further, environmental OP values can be expressed in two ways: as the OP normalised to
123 the volume of air containing a certain concentration of PM, or as the OP normalised to the mass of

124 particles, representing the intrinsic OP of the PM analysed. In addition to the variety of existing
125 methods, it is also important to emphasize that there is no unique way of PM collection. PM can be
126 collected on different types of filters using high and low-volume samplers. This method's main
127 disadvantages are poor particle recovery and particle aging, which leads to a certain kind of bias. In
128 order to minimize sampling errors and obtain the most accurate experimental data, various methods of
129 particle collection have been introduced, such as Versatile Aerosol Concentration Enrichment System
130 (VACES) [15], Particle Into Liquid Sampler (PILS) [16], Particle into Liquid Quencher (PINQ) [17],
131 samplers based on the condensation of particles, and Micro-Orifice Uniform Deposition Impactor
132 (MOUDI) for size-segregated samples [18]. However, automation and online measurements have
133 been a growing area of study, as they have the potential to significantly reduce analysis time, materials
134 and would also help to obtain data with better time resolution [19-21]. Taking into account all above
135 mention, these methods usually reveal a different response to the chemical constituents of PM, and
136 they differ greatly in sensitivity and application. Also, chemical composition and physical properties
137 could affect OP size distribution. Therefore, no method can define the total OP of measured PM, so it
138 is always better to combine them.
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140 **3. What we know about source apportionment**

141 The major objective of source apportionment (SA) models in the atmospheric sciences is to
142 determine which specific sources of pollution contribute what percentage of total air pollution. In the
143 literature, three different approaches to source apportionment have been documented.

144 According to the first approach, the sources are identified, using different methods based on
145 processing monitoring data. The way the data is processed with this approach generally results in
146 minor mathematical artifacts, considering the simplicity of the data processing. With this method, for
147 example, the location of specific sources of pollution can be determined by simply correlating wind
148 speed with measured components [22]. The second approach is relatively more complex and enables
149 simulating aerosol emission, generation, transport, and deposition using emission inventories and/or
150 dispersion models [23]. Since an emission inventory is defined as the quantity of pollutants released
151 into the atmosphere, which is not always available, a lack of this data limits these methods.
152 Nevertheless, these methods may assist in identifying important sources of pollution, which may be
153 significant for adopting various regulatory measures. Finally, the third approach represents statistical
154 analyses of PM chemical data obtained from receptor locations (receptor models), and represents the
155 most complex approach. Receptor modeling assumes mass and species conservation and uses a mass
156 balance analysis to identify and apportion airborne PM sources. Therefore, the primary objective of
157 receptor models is to identify the possible sources of PM and to obtain data on their contributions to
158 the bulk PM mass. Even human exposure to these pollution components has been evaluated to assess
159 their health effects and risks [24-26]. Thus the information provided by receptor models is key to the
160 design of effective mitigation strategies on the local- and meso-scale. In the literature, a variety of
161 statistical models and modeling approaches depending on the knowledge required before receptor
162 modeling can be found [27].

163 An important step in obtaining information that is crucial for developing air quality
164 management strategies is the quantitative distribution of pollutants to their specific sources. Previous
165 source apportionment studies are based mostly on PM_{2.5} and PM₁₀, while the positive matrix

166 factorization (PMF) and related methods, such as principle component analysis (PCA), multilinear
167 regression (MLR), UNIMAX and chemical mass balance (CMB), were the most frequently used. A
168 large number of studies have established distributions for a restricted number of chemical components
169 included in particles, such as heavy metals, carbonaceous, some specific organic tracers and water-
170 soluble species, in addition to PM distributions. Hopke et al.[28] summarised in SA review that
171 research conducted on PM_{2.5} and PM₁₀ samples had provided information on the apportionments that
172 define nine pollution sources. These sources are defined as:

- 173 • Inorganic source - sulfate, nitrate, and mixed secondary inorganic aerosol (SIA)
- 174 • Dust – It is the collective term for crustal material, which includes both natural soil and
175 desert dust
- 176 • Sea salt - this source usually contains Na and Cl
- 177 • Traffic - both exhaust and non-exhaust emissions
- 178 • Industry - this source mainly contains different metals characteristic of areas burdened
179 by different industrial activities
- 180 • Biomass burning - mix of several different sources (cooking, heating, biomass
181 burning...)
- 182 • Coal/oil combustion
- 183 • Other - SOA or uncalculated mass depending on the examined location/s

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185 Based on previous researches, the application of SA is important for several reasons; first of all, the
186 results of SA allow insight into the dominant sources of pollution, which can help develop strategies
187 and regulations that would contribute to improving air quality. Then, defining the source of pollution
188 and knowing the concentrations of specific components characteristic of that source can help in health-
189 oriented research.

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191 **4. Source apportionment of oxidative potential**

192 In contrast to many source apportionment of PM studies conducted worldwide, there is a limited
193 number of SA studies applied to oxidative potential. According to current literature data, about thirty
194 studies dealt with this issue, Table 1. Although this represents a small number of scientific papers that
195 would allow writing a literature review, this paper aims to point out the importance of this topic and
196 state the advantages and disadvantages of this approach.

197 Source apportionment of estimated OP values resulting from field campaigns has shown
198 differences among assays and sites studied, along with high temporal and spatial variability in each
199 site. Studies conducted to date have examined the toxicity of PM collected mostly in urban areas,
200 including locations impacted by nearby roads, airports, harbours, power plants and specific local and
201 regional sources. In contrast, few studies were conducted in rural and industrial sites [29-33].
202 Furthermore, the greatest emphasis was applied to PM_{2.5}, while only a few studies investigated the
203 association of OP of quasi-ultra-fine and coarse particles with potential sources [32, 34-41]. In support
204 of the fact that these studies are still in the development phase and require greater attention, the fact
205 that so far, the largest number of studies has been conducted in China, somewhat fewer in the USA,
206 and only a few studies in Europe.

Table 1. Source apportionment of PM studies related to OP conducted worldwide

	Type of site	PM	Sampling duration	Source contribution to OP
42]	Peri-urban background and urban	2.5	Mar - May 2012	Secondary aerosols, Zn source, Al source, Pb source and Fe source
29]	3 urban and 2 rural sites	2.5	Jun 2012 - Sep 2013	Biomass burning, secondary aerosols, vehicle and mineral dust
43]	Urban	2.5	Jun 2012 - Apr 2013	Biomass burning, light duty and heavy duty vehicles
30]	7 different urban and rural	2.5	Jun 2012 - Mar 2013	Biomass burning, secondary aerosols, traffic
44]	3 urban	2.5	May 2015 - Apr 2016	Biomass burning, secondary aerosols, vehicles, coal combustion, industry
45]	Urban	2.5	Mar 2012 - Mar 2013	Biomass burning, traffic, coal combustion, waste incineration
31]	Industrial	2.5	Jan-Mar 2018	Biomass burning, vehicles, crustal material, industry, secondary sulphate, sea spray
46]	Urban background	2.5	Jun - Sep 2017, Feb - Mar 2018	Biomass burning, secondary aerosols, vehicles
47]	Urban	2.5	May 2015 - Apr 2016	Traffic, dust, coal combustion, industry, secondary sulphate
48]	Urban	2.5	Sep 2011 - Aug 2012	Biomass burning, secondary aerosols, secondary sulphate, marine vessels
49]	Urban	2.5	Apr - Dec 2017, May - Jun 2017	Vehicle, dust, coal combustion, industry, secondary sulphate, secondary nitrate, metals
50]	Suburban	2.5	winter and spring 2010-2011	Biomass burning, traffic, light duty and heavy duty vehicles, industry,
	Suburban	2.5	Mar - Dec 2016	Metals, aromatic substances, humic-like, protein-like substances

51]				
52]	urban	2.5	Nov - Dec 2016,	Biomass burning, secondary aerosols, vehicle, land fossil fuel combustion
53]	urban	2.5	Sep 2011 - Avg 2012	Biomass burning, secondary aerosols, vehicle, secondary sulphate, marine vessels, metals
54]	2 urban	2.5	15 days in Feb 2019	Secondary aerosols, vehicle, mixed sources
55]	rural	2.5	Aug 2016, Jan - Feb 2017	Biomass burning, vehicle, mineral dust, coal combustion, secondary sulphate, secondary nitrate
33]	3 urban background, rural and road	2.5	May 2018 - May 2019	Biomass burning, secondary aerosols, vehicle, dust, secondary sulphate, ship emission, secondary nitrate, agricultural emission
56]	urban	2.5	Jan 2 nd to 16 th , Apr 7 th to 23 rd , July 3 rd to 18 th , Oct 12 th to 28 th 2017	Primary biomass burning WSOC, other WSOC primary combustion, transition metal ions, biomass burning SOC, aromatic SOC, the aged biogenic SOC
	Type of site	PM	Sampling duration	Source contribution to OP
36]	2 urban and one urban background	<0.25	Jun - Oct 2014	Secondary aerosols, light duty and heavy duty vehicles
34]	Urban-traffic and urban background	0.49	Jan - Mar 2013, May - Jul 2013	Biomass burning, traffic
35]	Urban and suburban	0.18, 2.5	Jul 2012 - Feb 2013	Secondary aerosols, vehicles, wood smoke, crustal materials, primary biogenic source
38]	2 urban	1, 2.5	Nov 2014, Jan-Feb 2015	Biomass burning, secondary aerosols, traffic, coal combustion, cooking
37]	Urban	2.5, 2.5-10	July 2016 to July 2017	Biomass burning, low volatility oxygenated organic aerosol, Hydrocarbon-like organic aerosol
32]	Urban, rural, road side, urban background	2.5, 10	Entire year 2013, Jan-Sep 2014	Biomass burning, secondary aerosols, traffic, crustal material
	Urban background	2.5, 10	Nov 2016 – Nov 2017	Biomass burning, vehicle, crustal material, secondary sulphate, sea spray, secondary

41]				nitrate, carbonates
57]	Urban	10	Nov 2013 - Oct 2014	Biomass burning and traffic
39]	14 urban	10	2003 - 2018	Biomass burning, secondary aerosols, vehicles, dust, primary biogenic, secondary nitrate
40]	Urban	10	Dec 2019 - Mar 2020, May -Aug 2020	Secondary aerosols, traffic, soil and resuspended dust, industry
58]	Urban	TSP	Jan - Mar, Apr - June, Oct, Nov 2016, Jan 2017	Biomass burning, secondary sulphate, ship emission, land fossil fuel combustion

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220 In the majority of SA of OP studies, the oxidative potential was measured by applying the DTT
221 assay. However, comparing the results obtained in different studies using this assay may be
222 questionable, considering that there is no standardized protocol for the DTT assay. Filter extraction
223 was mainly done by 30 min sonication in ultra-pure water, but the concentrations of DTT and DTNB
224 were in the wide range. DTT concentrations ranged between 0.1 mM to 10 mM, while the
225 concentrations of DTNB were between 0.2 mM and 10 mM. Also, in most of the studies, before
226 adding DTNB, trichloroacetic acid and Tris-HCl buffer containing EDTA were added, while in a few
227 studies, this step was avoided. From the above mentioned, it can be concluded that one of the first
228 steps is determining the detailed procedure for applying the DTT assay.

229 A detailed analysis of the existing literature showed that the largest contribution of ROS comes
230 primarily from biomass burning, secondary organic aerosol and traffic/vehicles. Given that not all
231 studies presented the contribution of a certain source of ROS in percentages, it can roughly be said that
232 the association of biomass burning ranged from 9 to 97%. Source apportionment of SOA's
233 contribution was 6 to 67%, while the traffic/vehicles source fell between 16 to 88%. The greatest
234 contribution of biomass burning to the overall OP was recorded during winter when the expected
235 pollution was the highest. On the other hand, SOA and traffic were the most important contributing
236 sources recorded during the summer months. Other sources that were also found to contribute to the
237 OP were secondary sulfates, secondary nitrates and dust; their contribution to OP was lower or equal
238 to 30% collectively. Also, it was observed that depending on the characteristics of the measurement
239 site and the influence of local sources, other potential sources contributing to higher concentrations of
240 ROS were also determined (industry, ship emission, coal/oil combustion, crustal materials and, etc.).
241 Daellenbach et al. [32] found that the major sources contributing to the mass and OP were different.
242 The PM mass was mainly supplied by the secondary inorganic components, crustal material and
243 secondary biogenic organic aerosols, while OP was mainly assigned to the fine-mode SOA from
244 residential biomass burning and coarse-mode metals from vehicular non-exhaust emissions. At the
245 urban roadside, OP PM₁₀ was found to be dominated by non-exhaust vehicular emissions (61%–88%),
246 mainly in the coarse mode. At the rural background site, anthropogenic SOA dominated OP PM₁₀
247 (33%–67%). In more pristine environments, such as alpine valleys, which are strongly affected by
248 residential heating during winter, biomass burning organic aerosol (BBOA) was significant OP source
249 in PM₁₀ fraction (7%–25%; 77%–97% during pollution events). A study conducted in France analysed
250 PM₁₀ filters collected over 15 years at 14 different locations, including urban, traffic and Alpine valley
251 site [39]. This study also highlights one aspect of SA OP complexity since the OP was measured using
252 two different probes. Hence different types of chemical compounds were picked up with different
253 probes and thus, different outcome from SA were established for the same samples. The primary road
254 traffic, biomass burning, dust, methanesulfonic acid rich (MSA-rich), and primary biogenic sources
255 had distinct positive redox activity towards the OP_{DTT} assay, whereas biomass burning and road traffic
256 sources only displayed significant activity for the OP_{AA} assay. The daily median source contribution to
257 the total OP_{DTT} highlighted the dominant influence of the primary road traffic source. On the other
258 hand, biomass burning and road traffic sources contributed evenly to the observed OP_{AA}. A study
259 conducted in an industrial area in Italy further confirmed that the SA of PM mass and OP do not
260 necessarily overlap. For example, industry emission did not significantly contribute to the mass but
261 had a significant contribution to the OP, whereas an opposite trend was observed for secondary
262 sulphates [31]. Contrary to these findings, PMF results obtained at a rural site in Northwest China

263 reported that biomass burning was among the major contributors to the mass and the OP in winter
264 [55]. Secondary nitrates were a significant OP source during winter, while secondary sulphates
265 dominated during summer. Altuwayjiri et al. [40] found that dust, SOA, local industrial activities,
266 petroleum refineries, and traffic emissions were the four most significant identified sources of OP
267 31%, 20%, 19%, and 17%, respectively, in the arid area of Riyadh. Another study in Italy further
268 confirmed that the SOA varies seasonally and that the SA of OP is different in different mass
269 fractions, namely PM_{2.5} and PM₁₀ [41].

270 SA models also showed significant divergence in the contribution of different sources of OP vs.
271 PM mass. In other words, OP and PM mass can have common contribution sources, but their
272 contribution differs significantly. For example, Wang et al. found that the contribution of agricultural
273 activities at the rural site for PM_{2.5} mass was 12% but for cellular OP was 62% at the same location
274 [33]. For this reason, the application of SA PM mass and OP does not necessarily lead to the same
275 results, which is another indicator of the observation that the particular sources that contribute to a
276 lesser extent to PM mass can overshadow the impact of that that source to their toxicity. It is necessary
277 to examine the specific species that contribute to the increased OP to get a better insight into the
278 specifics of source apportionment of OP.

279

280 **5. Conclusion**

281 Since PM toxicity is a poorly understood phenomenon, the first step in the holistic
282 understanding of PM toxicity could be measuring oxidative potential of PM and their connection with
283 specific sources. Detailed analyses, with a well-designed and uniform strategy of sampling,
284 measurement, and application of a certain SA technique, could significantly help in understanding this
285 issue. However, regardless of the advantages of this approach, certain limitations still need to be
286 overcome to improve future research. Primarily it refers to standardizing sample extraction and
287 acellular assays to determine OP. Also, when filters are analysed, it is known that particles, that may
288 carry short-lived ROS, are mostly gone from the sample. In light of this, it appears that a combination
289 of online and offline methods is best suitable for understanding the various ROS. One should then,
290 consider the uncertainties arising from the application of the SA model. Even though it is known that
291 PM_{2.5} penetrates to the deeper parts of the lungs and has a greater impact on human health, it is
292 necessary to examine the effects of PM₁₀ in more detail.

293

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305 **References**

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- 308 [1] Poschl, U., Atmospheric aerosols: composition, transformation, climate and health effects,
309 *Angew Chem Int Ed Engl*, *44*. (2005), 46, pp. 7520-40, DOI No. 10.1002/anie.200501122
- 310 [2] Sun, Z.,D. Zhu, Exposure to outdoor air pollution and its human health outcomes: A scoping
311 review, *PLOS ONE*, *14*. (2019), 5, p. e0216550, DOI No. 10.1371/journal.pone.0216550
- 312 [3] Poprac, P., *et al.*, Targeting Free Radicals in Oxidative Stress-Related Human Diseases,
313 *Trends in Pharmacological Sciences*, *38*. (2017), 7, pp. 592-607, DOI No.
314 <https://doi.org/10.1016/j.tips.2017.04.005>
- 315 [4] Dasgupta, A.,K. Klein, *Chapter 1 - Introduction to Free Radicals and the Body's Antioxidant*
316 *Defense*, in: *Antioxidants in Food, Vitamins and Supplements*, (Ed., Editor^Editors), Elsevier:
317 San Diego. 2014, pp. 1-18.
- 318 [5] Dellinger, B., *et al.*, Role of Free Radicals in the Toxicity of Airborne Fine Particulate Matter,
319 *Chemical Research in Toxicology*, *14*. (2001), 10, pp. 1371-1377, DOI No.
320 10.1021/tx010050x
- 321 [6] Bates, J.T., *et al.*, Review of Acellular Assays of Ambient Particulate Matter Oxidative
322 Potential: Methods and Relationships with Composition, Sources, and Health Effects,
323 *Environmental Science & Technology*, *53*. (2019), 8, pp. 4003-4019, DOI No.
324 10.1021/acs.est.8b03430
- 325 [7] Borm, P.J., *et al.*, Oxidant generation by particulate matter: from biologically effective dose to
326 a promising, novel metric, *Occupational and Environmental Medicine*, *64*. (2007), 2, pp. 73-4,
327 DOI No. <http://dx.doi.org/10.1136/oem.2006.029090>
- 328 [8] Fuller, S.J., *et al.*, Comparison of on-line and off-line methods to quantify reactive oxygen
329 species (ROS) in atmospheric aerosols, *Atmospheric Environment*, *92*. (2014), pp. 97-103,
330 DOI No. <https://doi.org/10.1016/j.atmosenv.2014.04.006>
- 331 [9] Crobeddu, B., *et al.*, Oxidative potential of particulate matter 2.5 as predictive indicator of
332 cellular stress, *Environmental Pollution*, *230*. (2017), pp. 125-133, DOI No.
333 <https://doi.org/10.1016/j.envpol.2017.06.051>
- 334 [10] Daher, N., *et al.*, Oxidative potential and chemical speciation of size-resolved particulate
335 matter (PM) at near-freeway and urban background sites in the greater Beirut area, *Science of*
336 *The Total Environment*, *470-471*. (2014), pp. 417-426, DOI No.
337 <https://doi.org/10.1016/j.scitotenv.2013.09.104>
- 338 [11] Mirowsky, J.E., *et al.*, In vitro and in vivo toxicity of urban and rural particulate matter from
339 California, *Atmospheric Environment*, *103*. (2015), pp. 256-262, DOI No.
340 <https://doi.org/10.1016/j.atmosenv.2014.12.051>
- 341 [12] Carere, A., *et al.*, In vitro toxicology methods: impact on regulation from technical and
342 scientific advancements, *Toxicol Lett*, *127*. (2002), 1-3, pp. 153-60, DOI No. 10.1016/s0378-
343 4274(01)00495-7
- 344 [13] Driscoll, K.E., *et al.*, Intratracheal instillation as an exposure technique for the evaluation of
345 respiratory tract toxicity: uses and limitations, *Toxicol Sci*, *55*. (2000), 1, pp. 24-35, DOI No.
346 10.1093/toxsci/55.1.24
- 347 [14] Cho, C.-C., *et al.*, In Vitro and In Vivo Experimental Studies of PM_{2.5} on Disease
348 Progression, *International Journal of Environmental Research and Public Health*, *15*. (2018),
349 7, p. 1380
- 350 [15] Kim, S., *et al.*, Versatile aerosol concentration enrichment system (VACES) for simultaneous
351 in vivo and in vitro evaluation of toxic effects of ultrafine, fine and coarse ambient particles
352 Part I: Development and laboratory characterization, *Journal of Aerosol Science*, *32*. (2001),
353 11, pp. 1281-1297, DOI No. [https://doi.org/10.1016/S0021-8502\(01\)00057-X](https://doi.org/10.1016/S0021-8502(01)00057-X)
- 354 [16] Sorooshian, A., *et al.*, Modeling and Characterization of a Particle-into-Liquid Sampler
355 (PILS), *Aerosol Science and Technology*, *40*. (2006), 6, pp. 396-409, DOI No.
356 10.1080/02786820600632282
- 357 [17] Brown, R.A., *et al.*, An instrument for the rapid quantification of PM-bound ROS: the Particle
358 Into Nitroxide Quencher (PINQ), *Atmos. Meas. Tech.*, *12*. (2019), 4, pp. 2387-2401, DOI No.
359 10.5194/amt-12-2387-2019

- 360 [18] Keywood, M.D., *et al.*, Relationships between size segregated mass concentration data and
361 ultrafine particle number concentrations in urban areas, *Atmospheric Environment*, 33. (1999),
362 18, pp. 2907-2913, DOI No. [https://doi.org/10.1016/S1352-2310\(99\)00102-8](https://doi.org/10.1016/S1352-2310(99)00102-8)
- 363 [19] Fang, T., *et al.*, A semi-automated system for quantifying the oxidative potential of ambient
364 particles in aqueous extracts using the dithiothreitol (DTT) assay: Results from the
365 Southeastern Center for Air Pollution and Epidemiology (SCAPE), *Atmospheric Measurement*
366 *Techniques*, 8. (2015), 1, pp. 471-482, DOI No. 10.5194/amt-8-471-2015
- 367 [20] Gao, D., *et al.*, A method for measuring total aerosol oxidative potential (OP) with the
368 dithiothreitol (DTT) assay and comparisons between an urban and roadside site of water-
369 soluble and total OP, *Atmospheric Measurement Techniques*, 10. (2017), 8, pp. 2821-2835,
370 DOI No. 10.5194/amt-10-2821-2017
- 371 [21] Salana, S., *et al.*, A semi-automated instrument for cellular oxidative potential evaluation
372 (SCOPE) of water-soluble extracts of ambient particulate matter, *Atmos. Meas. Tech.*, 14.
373 (2021), 12, pp. 7579-7593, DOI No. 10.5194/amt-14-7579-2021
- 374 [22] Henry, R.C., *et al.*, Locating nearby sources of air pollution by nonparametric regression of
375 atmospheric concentrations on wind direction, *Atmospheric Environment*, 36. (2002), 13, pp.
376 2237-2244, DOI No. [https://doi.org/10.1016/S1352-2310\(02\)00164-4](https://doi.org/10.1016/S1352-2310(02)00164-4)
- 377 [23] Eldering, A., G.R. Cass, Source-oriented model for air pollutant effects on visibility, *Journal*
378 *of Geophysical Research: Atmospheres*, 101. (1996), D14, pp. 19343-19369, DOI No.
379 <https://doi.org/10.1029/95JD02928>
- 380 [24] Hopke, P.K., *et al.*, PM source apportionment and health effects: 1. Intercomparison of source
381 apportionment results, *Journal of Exposure Science & Environmental Epidemiology*, 16.
382 (2006), 3, pp. 275-286, DOI No. 10.1038/sj.jea.7500458
- 383 [25] Ilacqua, V., *et al.*, Source apportionment of population representative samples of PM_{2.5} in
384 three European cities using structural equation modelling, *Science of The Total Environment*,
385 384. (2007), 1, pp. 77-92, DOI No. <https://doi.org/10.1016/j.scitotenv.2007.06.020>
- 386 [26] Watson, J.G., *et al.*, Receptor modeling application framework for particle source
387 apportionment, *Chemosphere*, 49 9. (2002), pp. 1093-136
- 388 [27] Viana, M., *et al.*, Source apportionment of particulate matter in Europe: A review of methods
389 and results, *Journal of Aerosol Science*, 39. (2008), 10, pp. 827-849, DOI No.
390 <https://doi.org/10.1016/j.jaerosci.2008.05.007>
- 391 [28] Hopke, P.K., *et al.*, Global review of recent source apportionments for airborne particulate
392 matter, *Science of The Total Environment*, 740. (2020), p. 140091, DOI No.
393 <https://doi.org/10.1016/j.scitotenv.2020.140091>
- 394 [29] Verma, V., *et al.*, Reactive oxygen species associated with water-soluble PM_{2.5} in the
395 southeastern United States: Spatiotemporal trends and source apportionment, *Atmospheric*
396 *Chemistry and Physics*, 14. (2014), 23, pp. 12915-12930, DOI No.
397 <https://doi.org/10.5194/acp-14-12915-2014>
- 398 [30] Fang, T., *et al.*, Oxidative potential of ambient water-soluble PM_{2.5} in the southeastern
399 United States: Contrasts in sources and health associations between ascorbic acid (AA) and
400 dithiothreitol (DTT) assays, *Atmospheric Chemistry and Physics*, 16. (2016), 6, pp. 3865-
401 3879, DOI No. 10.5194/acp-16-3865-2016
- 402 [31] Cesari, D., *et al.*, Source Apportionment of PM_{2.5} and of its Oxidative Potential in an
403 Industrial Suburban Site in South Italy, *Atmosphere*, 10. (2019), 12, p. 758
- 404 [32] Daellenbach, K.R., *et al.*, Sources of particulate-matter air pollution and its oxidative potential
405 in Europe, *Nature*, 587. (2020), 7834, pp. 414-419, DOI No. 10.1038/s41586-020-2902-8
- 406 [33] Wang, Y., *et al.*, Sources of cellular oxidative potential of water-soluble fine ambient
407 particulate matter in the Midwestern United States, *Journal of Hazardous Materials*, 425.
408 (2022), p. 127777, DOI No. <https://doi.org/10.1016/j.jhazmat.2021.127777>
- 409 [34] Argyropoulos, G., *et al.*, Source apportionment of the redox activity of urban quasi-ultrafine
410 particles (PM_{0.49}) in Thessaloniki following the increased biomass burning due to the
411 economic crisis in Greece, *Science of The Total Environment*, 568. (2016), pp. 124-136, DOI
412 No. <https://doi.org/10.1016/j.scitotenv.2016.05.217>
- 413 [35] Shirmohammadi, F., *et al.*, The relative importance of tailpipe and non-tailpipe emissions on
414 the oxidative potential of ambient particles in Los Angeles, CA, *Faraday Discussions*, 189.
415 (2016), 0, pp. 361-380, DOI No. <http://doi.org/10.1039/c5fd00166h>
- 416 [36] Saffari, A., *et al.*, Impact of primary and secondary organic sources on the oxidative potential
417 of quasi-ultrafine particles (PM_{0.25}) at three contrasting locations in the Los Angeles Basin,

- 418 *Atmospheric Environment*, 120. (2015), pp. 286-296, DOI No.
419 <https://doi.org/10.1016/j.atmosenv.2015.09.022>
- 420 [37] Paraskevopoulou, D., *et al.*, Yearlong variability of oxidative potential of particulate matter in
421 an urban Mediterranean environment, *Atmospheric Environment*, 206. (2019), pp. 183-196,
422 DOI No. <https://doi.org/10.1016/j.atmosenv.2019.02.027>
- 423 [38] Zhou, J., *et al.*, Predominance of secondary organic aerosol to particle-bound reactive oxygen
424 species activity in fine ambient aerosol, *Atmos. Chem. Phys.*, 19. (2019), 23, pp. 14703-14720,
425 DOI No. 10.5194/acp-19-14703-2019
- 426 [39] Weber, S., *et al.*, Source apportionment of atmospheric PM10 oxidative potential: synthesis of
427 15 year-round urban datasets in France, *Atmos. Chem. Phys.*, 21. (2021), 14, pp. 11353-11378,
428 DOI No. 10.5194/acp-21-11353-2021
- 429 [40] Altuwayjiri, A., *et al.*, Impact of different sources on the oxidative potential of ambient
430 particulate matter PM10 in Riyadh, Saudi Arabia: A focus on dust emissions, *Science of The*
431 *Total Environment*, 806. (2022), p. 150590, DOI No.
432 <https://doi.org/10.1016/j.scitotenv.2021.150590>
- 433 [41] Giannossa, L.C., *et al.*, Inter-annual variability of source contributions to PM10, PM2.5, and
434 oxidative potential in an urban background site in the central mediterranean, *Journal of*
435 *Environmental Management*, 319. (2022), p. 115752, DOI No.
436 <https://doi.org/10.1016/j.jenvman.2022.115752>
- 437 [42] Liu, Q., *et al.*, Oxidative Potential and Inflammatory Impacts of Source Apportioned Ambient
438 Air Pollution in Beijing, *Environmental Science & Technology*, 48. (2014), 21, pp. 12920-
439 12929, DOI No. 10.1021/es5029876
- 440 [43] Bates, J.T., *et al.*, Reactive Oxygen Species Generation Linked to Sources of Atmospheric
441 Particulate Matter and Cardiorespiratory Effects, *Environ Sci Technol*, 49. (2015), 22, pp.
442 13605-12, DOI No. 10.1021/acs.est.5b02967
- 443 [44] Liu, W., *et al.*, Oxidative potential of ambient PM2.5 in the coastal cities of the Bohai Sea,
444 northern China: Seasonal variation and source apportionment, *Environmental Pollution*, 236.
445 (2018), pp. 514-528, DOI No. <https://doi.org/10.1016/j.envpol.2018.01.116>
- 446 [45] Ma, Y., *et al.*, Sources and oxidative potential of water-soluble humic-like substances
447 (HULISWS) in fine particulate matter (PM2.5) in Beijing, *Atmos. Chem. Phys.*, 18. (2018), 8,
448 pp. 5607-5617, DOI No. 10.5194/acp-18-5607-2018
- 449 [46] Taghvaei, S., *et al.*, Source apportionment of the oxidative potential of fine ambient
450 particulate matter (PM2.5) in Athens, Greece, *Science of The Total Environment*, 653. (2019),
451 pp. 1407-1416, DOI No. <https://doi.org/10.1016/j.scitotenv.2018.11.016>
- 452 [47] Yu, S., *et al.*, Characteristics and oxidative potential of atmospheric PM2.5 in Beijing: Source
453 apportionment and seasonal variation, *Science of The Total Environment*, 650. (2019), pp.
454 277-287, DOI No. <https://doi.org/10.1016/j.scitotenv.2018.09.021>
- 455 [48] Ma, Y., *et al.*, Optical properties, source apportionment and redox activity of humic-like
456 substances (HULIS) in airborne fine particulates in Hong Kong, *Environmental Pollution*,
457 255. (2019), p. 113087, DOI No. <https://doi.org/10.1016/j.envpol.2019.113087>
- 458 [49] Wang, Y., *et al.*, Study on the oxidation potential of the water-soluble components of ambient
459 PM2.5 over Xi'an, China: Pollution levels, source apportionment and transport pathways,
460 *Environment International*, 136. (2020), p. 105515, DOI No.
461 <https://doi.org/10.1016/j.envint.2020.105515>
- 462 [50] Moufarrej, L., *et al.*, Assessment of the PM2.5 oxidative potential in a coastal industrial city in
463 Northern France: Relationships with chemical composition, local emissions and long range
464 sources, *Science of The Total Environment*, 748. (2020), p. 141448, DOI No.
465 <https://doi.org/10.1016/j.scitotenv.2020.141448>
- 466 [51] Ma, X., *et al.*, The Relative Contributions of Different Chemical Components to the Oxidative
467 Potential of Ambient Fine Particles in Nanjing Area, *International journal of environmental*
468 *research and public health*, 18. (2021), 6, p. 2789, DOI No. 10.3390/ijerph18062789
- 469 [52] Campbell, S.J., *et al.*, Atmospheric conditions and composition that influence PM2.5 oxidative
470 potential in Beijing, China, *Atmos. Chem. Phys.*, 21. (2021), 7, pp. 5549-5573, DOI No.
471 10.5194/acp-21-5549-2021
- 472 [53] Cheng, Y., *et al.*, Pollutants from primary sources dominate the oxidative potential of water-
473 soluble PM2.5 in Hong Kong in terms of dithiothreitol (DTT) consumption and hydroxyl
474 radical production, *Journal of Hazardous Materials*, 405. (2021), p. 124218, DOI No.
475 <https://doi.org/10.1016/j.jhazmat.2020.124218>

- 476 [54] Ahmad, M., *et al.*, Chemical characteristics, oxidative potential, and sources of PM_{2.5} in
477 wintertime in Lahore and Peshawar, Pakistan, *Journal of Environmental Sciences*, 102.
478 (2021), pp. 148-158, DOI No. <https://doi.org/10.1016/j.jes.2020.09.014>
- 479 [55] Li, J., *et al.*, In-vitro oxidative potential and inflammatory response of ambient PM_{2.5} in a
480 rural region of Northwest China: Association with chemical compositions and source
481 contribution, *Environmental Research*, 205. (2022), p. 112466, DOI No.
482 <https://doi.org/10.1016/j.envres.2021.112466>
- 483 [56] Yu, Q., *et al.*, Oxidative potential associated with water-soluble components of PM_{2.5} in
484 Beijing: The important role of anthropogenic organic aerosols, *Journal of Hazardous*
485 *Materials*, 433. (2022), p. 128839, DOI No. <https://doi.org/10.1016/j.jhazmat.2022.128839>
- 486 [57] Weber, S., *et al.*, An apportionment method for the oxidative potential of atmospheric
487 particulate matter sources: application to a one-year study in Chamonix, France, *Atmos. Chem.*
488 *Phys.*, 18. (2018), 13, pp. 9617-9629, DOI No. 10.5194/acp-18-9617-2018
- 489 [58] Wang, J., *et al.*, Source apportionment of water-soluble oxidative potential in ambient total
490 suspended particulate from Bangkok: Biomass burning versus fossil fuel combustion,
491 *Atmospheric Environment*, 235. (2020), p. 117624, DOI No.
492 <https://doi.org/10.1016/j.atmosenv.2020.117624>

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