An interlaboratory comparison to quantify oxidative potential measurement in aerosol particles: challenges and recommendations for harmonisation

Pamela A. Dominutti[1], Jean-Luc Jaffrezo[1], Anouk Marsal[1], Takoua Mhadhbi[1], Rhabira Elazzouzi[1], Camille Rak[1], Fabrizia Cavalli[2], Jean-Philippe Putaud[2], Aikaterini Bougiatioti[3], Nikolaos Mihalopoulos[3,4], Despina Paraskevopoulou[3], Ian Mudway[5], Athanasios Nenes[6§], Kaspar R. Daellenbach[7], Catherine Banach[8], Steven J. Campbell[9], Hana Cigánková[10], Daniele Contini[11], Greg Evans[12], Maria Georgopoulou[6], Manuella Ghanem[13], Drew A. Glencross[5], Maria Rachele Guascito[11,14], Hartmut Herrmann[15], Saima Iram[16], Maja Jovanović[17], Milena Jovašević-Stojanoić[17], Markus Kalberer[18], Ingeborg M. Kooter[19†], Suzanne E. Paulson[8], Anil Patel[20#*], Esperanza Perdrix[21], Maria Chiara Pietrogrande[22], Pavel Mikuška[10], Jean-Jacques Sauvain[23], Katerina Seitanidi[6], Pourya Shahpoury[24], Eduardo J. dos S. Souza[15], Sarah Steimer[20#], Svetlana Stevanovic[16], Guillaume Suarez[23], P. S. Ganesh Subramanian[25], Battist Utinger[18], Marloes F. van Os[19], Vishal Verma[25], Xing Wang[12], Rodney J. Weber[26], Yuhan Yang[26], Xavier Querol[27], Gerard Hoek[28], Roy M. Harrison[29+], and Gaëlle Uzu[1*].

[1] University Grenoble Alpes, CNRS, INRAE, IRD, INP-G, IGE (UMR 5001), 38000 Grenoble, France

[2] European Commission, Joint Research Centre (JRC), Ispra, Italy

[3] Institute for Environmental Research and Sustainable Development, National Observatory of Athens, Lofos Koufou, P. Penteli, Athens, 15236, Greece

[4] Environmental Chemical Processes Laboratory, Department of Chemistry, University of Crete, Heraklion, 71003, Greece.

[5] MRC Centre for Environment and Health, and the National Institute of Health Research, Health Protection Research Unit in Environmental Exposures and Health, Imperial College London, London, UK

[6] Center for the Study of Air Quality and Climate Change, Institute of Chemical Engineering Sciences, Foundation for Research and Technology Hellas, Patras, Greece 26504

[7] Laboratory of Atmospheric Chemistry, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland

[8] Department of Atmospheric and Oceanic Sciences, University of California at Los Angeles, 520 Portola Plaza, Los Angeles, California, 90095, United States

[9] MRC Centre for Environment and Health, Environmental Research Group, Imperial College London, 86 Wood Lane, London W12 0BZ, UK.

[10] Department of Environmental Analytical Chemistry, Institute of Analytical Chemistry, Czech Academy of Sciences, Veveří 97, 60200 Brno, Czech Republic

[11] Institute of Atmospheric Sciences and Climate, ISAC-CNR, Str. Prv. Lecce-Monteroni km 1.2, 73100 Lecce, Italy

[12] Southern Ontario Centre for Atmospheric Aerosol Research, University of Toronto, Toronto, M5S 3E5, Canada

38 [13] Department of Pollutant Metrology, Institut National de Recherche et de Sécurité (INRS), 54500 Vandœuvre-
39 lès-Nancy, France

40 [14] Department of Environmental and Biological Sciences and Technologies (DISTEBA), University of
41 Salento, Lecce 73100, Italy

42 [15] Atmospheric Chemistry Department (ACD), Leibniz Institute for Tropospheric Research (TROPOS),
43 Permoserstraße 15, 04318 Leipzig, Germany

44 [16] School of Engineering, Deakin University, VIC 3216, Australia

45 [17] Vinča Institute of Nuclear Sciences – National Institute of the Republic of Serbia, University of Belgrade,
46 11 351 Belgrade, Serbia

47 [18] Department of Environmental Sciences, University of Basel, 4056 Basel, Switzerland

48 [19] TNO Environmental Modelling, Sensing and Analysis, Princetonlaan 6-8, 3584 CB Utrecht, Netherlands

49 [20] Department of Environmental Science, Stockholm University, Stockholm, 11418, Sweden

50 [21] IMT Nord Europe, Institut Mines-Télécom, Univ. Lille, Centre for Energy and Environment, F-59000 Lille,
51 France

52 [22] Department of Chemical, Pharmaceutical and Agricultural Sciences, University of Ferrara, Via Fossato
53 di Mortara 17/19, 44121 Ferrara, Italy

54 [23] Center for Primary Care and Public Health (Unisanté), Department of Occupational and Environment Health
55 (DSTE), University of Lausanne, Switzerland

56 [24] Environmental and Life Sciences, Trent University, Peterborough, Canada

57 [25] Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 North
58 Mathews Avenue, Urbana, IL, 61801, United States

59 [26] School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, Georgia 30332,
60 United States

61 [27] Institute of Environmental Assessment and Water Research (IDAEA-CSIC), 08034 Barcelona, Spain

62 [28] Institute for Risk Assessment Sciences, Utrecht University, Utrecht, 3584CM, the Netherlands

63 [29] Division of Environmental Health and Risk Management, School of Geography Earth and Environmental
64 Sciences, Edgbaston, Birmingham, UK, B15 2TT, United Kingdom

65 † Deceased

66 [+] Also at: Department of Environmental Sciences, King Abdulaziz University, Jeddah, Saudi Arabia

67 [*] Now at: Bagchi School of Public Health, Ahmedabad University, Ahmedabad 380009, Gujarat, India

68 [#] Also at: Bolin Centre for Climate Research, Stockholm, 11418, Sweden

69 [§] Also at: Laboratory of Atmospheric Processes and their Impacts, Institute of Environmental Engineering, Ecole
70 Polytechnique Federale de Lausanne, Lausanne, Switzerland, 1015

71 *Corresponding author: gaelle.uzu@ird.fr

Abstract

This paper presents the findings from a collaborative interlaboratory comparison exercise designed to assess oxidative potential (OP) measurements conducted by 20 laboratories worldwide. This study represents an innovative effort as the first exercise specifically aimed at harmonising this type of OP assay, setting a new benchmark in the field.

Over the last decade, there has been a noticeable increase in OP studies, with numerous research groups investigating the effects of exposure to air pollution particles through the evaluation of OP levels. However, the absence of standardised methods for OP measurements has resulted in variability in results across different groups, rendering meaningful comparisons challenging. To address this issue, this study engages in an international effort to compare OP measurements using a simplified method (with a dithiothreitol (DTT) assay).

Here, we quantify the OP in liquid samples to focus on the protocol measurement itself, while future ILCs should aim to assess the full-chain process, including the sample extraction. We analyse the similarities and discrepancies observed in the results, identifying the critical parameters (such as the instrument used, the use of a simplified protocol, the delivery and analysis time) that could influence OP measurements, and provide recommendations for future studies and interlaboratory comparisons. Even if other crucial aspects, such as sampling PM methods, sample storage, extraction methods and conditions, and the evaluation of other OP assays, still need to be standardised. This collaborative approach enhances the robustness of the OP-DTT assay and paves the way for future studies to build on a unified framework. This pioneering work concludes that interlaboratory comparisons provide essential insights into the OP metric and are crucial to move toward the harmonisation of OP measurements.

1. Introduction

Over the last decade, many studies demonstrated associations between exposure to ambient air pollution and adverse human health outcomes (Hart et al., 2015; Laden et al., 2006; Lepeule et al., 2012; WHO, 2013, 2021). Adverse health effects attributable to particle matter (PM) are complex and diverse. Among environmental factors, PM is considered to be the largest contributor to morbidity and mortality globally (WHO, 2024). The casual mechanisms underpinning these adverse associations are diverse, with oxidative stress and inflammation (Leni et al., 2020; Li et al., 2003, Li et al.,2008), genomic alterations (Huang et al., 2022),damage to the nervous system function (Wilker et al., 2023), and epigenetic alterations, cognitive decline (Nicholson et al., 2022; Zare Sakhvidi et al., 2022), among others, all cited as potential contributing pathways. Across these broad domains, the capacity of particles and particle-derived chemicals to cause damaging biological oxidations appears to be oxidative stress ultimately response, both through the introduction of pro-oxidants and stable free radicals into the body, but also through secondary radical/oxidant generation through altered metabolism

106 and induction of inflammation (Li et al., 2008). By definition, oxidative stress is a condition where excess
107 production of reactive oxygen species (ROS) and nitrogen species (RNS) overwhelm endogenous antioxidant
108 defences (Shankar and Mehendale, 2014). Generally, ROS/RNS production in the cells is regulated within
109 physiological limits, through the actions of antioxidant enzymes (e.g. superoxide dismutase, catalase, etc), low
110 molecular weight water-soluble (e.g. glutathione, ascorbate) and fat-soluble (vitamin E) antioxidants (Alkoussa
111 et al., 2020). This antioxidant system plays a valuable key role by limiting ROS/RNS damage, which is associated
112 with cytotoxicity and the induction of inflammation due to changes in the cellular redox balance (Cassee et al.,
113 2013; Gao et al., 2020; Kelly and Fussell, 2017; Sies, 2018). The capacity of PM to invoke biological oxidations
114 has therefore been proposed as a proxy measure of their toxicity, and has been referred to as their oxidative
115 potential (OP); either that intrinsic to their possession of pro-oxidants, or encompassing their capacity more
116 wholistically to simulate ROS/RNS through interaction with cells (Ayres et al., 2008; Bates et al., 2015; Cho et
117 al., 2005; Sauvain et al., 2008; Uzu et al., 2011).

118 Consequently, the OP of PM is increasingly being studied as a potentially health-relevant metric to evaluate
119 effects due to exposure to PM, in addition to PM mass concentration, in multiple regions across the globe (Bates
120 et al., 2019; Bhattu et al., 2024; Daellenbach et al., 2017; Weichenthal et al., 2019). OP is a relatively simple
121 estimation of PM redox activity that reflects a complex interplay of all physico-chemical properties (chemical
122 composition, surface-area, solubility and particle size) contributing to the ROS/RNS generation and the
123 oxidation of target biomolecules, or probes. Implicit within this approach is the contention that not all
124 constituents of ambient PM are equally as harmful, and that those that drive damaging redox reactions, either
125 directly, or indirectly present a greater hazard. Thus, PM composition should be considered a factor more
126 directly linked to adverse health effects than PM mass concentration, highlighting the need to study additional
127 health-relevant metrics such as the OP (Park et al., 2018).

128 In last decades, there has been an increased interest in measuring and developing OP studies, applying different
129 in vivo or in vitro assays and aerosol characterisation techniques to estimate the main sources of OP related to
130 PM (Guascito et al., 2023), and attempting to integrate this metric into health studies. Several acellular chemical
131 methods have been applied for the estimation of the OP of atmospheric particles since these assays allow faster
132 measurement and are less labour-intensive than cell culture or in vivo methods (Bates et al., 2019). In addition,
133 these assays aim to mimic the interaction between PM and different lung antioxidants (e.g. glutathione,
134 ascorbate…, etc) during inhalation. The acellular assays which are most commonly applied include several
135 probe approaches based on antioxidants or surrogates, such as the dithiothreitol assay (DTT), ascorbic acid
136 assay (AA), glutathione assay (GSH), Ferric-Xylenol Orange assay (FOX), 9,10-bis (phenylethynyl) anthracene-
137 nitroxide (BPEAnit) ROS assay and 2,7-dichlorofluorescein assay (DCFH) for bound-particles. Molecular probes
138 display variable sensitivities to PM components due to their unique redox potentials and chemical reaction
139 routes, contributing to aerosol OP values. Therefore, it may be necessary to use several assays simultaneously
140 for a broader assessment of the chemical species in PM potentially triggering oxidative stress and to evaluate

which of these probes might be most indicative and closely linked to health effects. Furthermore, one of the main challenges within this rapidly expanding research field is the diversity of analytical methods and protocols used for OP each assay, which require standardised protocols to support synthesis across the evidence base (Ayres et al., 2008).

In 2008, a previous workshop gathered experts on OP and developed consensus statements addressing the importance of standardised samples, the comparison between oxidative potential tests, the formulation of consistent standard test protocols and the establishment of connections between OP tests and epidemiological findings as reliable predictors of adverse health outcome (Ayres et al., 2008). Despite more than 15 years having elapsed since that workshop, whilst protocols have matured, evolved, and proliferated worldwide, little concrete work has been performed regarding the harmonization and standardization of these methods.

One of the main objectives of the RI-URBANS European project (https://riurbans.eu/) is to bring accessible service tools to enhance air quality monitoring networks, including evaluating air pollution exposure. As OP has been proposed and recommended as a parameter to be measured in the proposal for a new European Air Quality Directive (Council of the European Union, 2024), an international OP interlaboratory comparison (ILC) was launched to assess the consistency of OP measurements between participants that apply different OP DTT protocols, hindering comparison of results obtained worldwide. The main goal of the ILC was to identify potential discrepancies in results (obtained with the OP DTT assay, one of the most common acellular assays used for measuring the OP) that may arise due to differences in experimental procedures, equipment, or analytical techniques. This ILC constitutes a first step to identify potential sources of variability, resulting in the enhancement of the overall accuracy, reliability and comparability of OP measurements.

This paper presents the setup and results of this first large ILC study based on the dithiothreitol (DTT) assay, with a large number of participants (20 groups). The first section includes a description of how a simplified protocol was obtained, along with the coordination/management of the ILC. Subsequently, the results are presented in the second section, combined with statistical analysis, both for the harmonized protocol and the "home" protocols of each participant. Finally, some major findings and recommendations are presented.

2. Intercomparison strategy

This ILC was proposed within the RI-URBANS European Project framework to evaluate the discrepancies and commonalities of OP measurements obtained by the different participating laboratories. The setup of the protocol was led by a working group of laboratories with considerable experience in oxidative potential: FORTH (The Foundation for Research and Technology – Hellas (FORTH, Greece), NOA (National Observatory of Athens, Greece), ICL (Imperial College of London, United Kingdom), IGE (Institute of Environmental Geosciences, France) and UoB (University of Birmingham, United Kingdom) (i.e. the "core group"). Considerations regarding sampling techniques of PM filters or monitoring strategic approaches are beyond the scope of this exercise.

174 Multiple OP assays are available; however, following a literature review, it was decided to prioritise the DTT
175 assay for this first ILC due to its widespread adoption and long-term application facilitating broad participation
176 from laboratories. The core group first produced a harmonised and simplified method, detailed in a
177 standardised operation procedure (SOP), that was integrated, implemented and tested by IGE, the organiser
178 for this ILC. This SOP is called the "RI-URBANS DTT SOP" in the following and is presented in detail in Section
179 2.2. Section 2.1 presents the selection procedure for some parameters of the DTT assay according to variations
180 observed in the literature. Sections 2.3 to 2.7 comprise different parts of the implementation of the ILC, along
181 with the procedure for data processing.

182

183 2.1 Testing the parameters for implementing the simplified RI-URBANS protocol

184 The simplified RI-URBANS DTT SOP was adapted from the original DTT protocols published in the early 2000s
185 (SOP1: Li et al., 2003, 2009; SOP2: Cho et al., 2005; SOP3: Kumagai et al., 2002; called SOP1, SOP2 and SOP3,
186 hereafter). The principle of the DTT assay relies on the production of superoxide radicals, with DTT acting as a
187 surrogate for cellular reducing agents. This probe contains thiol groups similar to GSH and subjects to oxidation,
188 forming stable cyclic disulphides by donating electrons to oxygen through intermediate redox-active species
189 from PM. In the assay proposed by Kumagai et al. (2002), PM is incubated with DTT and its rate of oxidation
190 over time is assessed through the use of 5,5′-dithiobis-(2-nitrobenzoic acid) (DTNB) with the reaction product
191 2-nitro-5-thiobenzoic acid (TNB), being detected at 412nm. Whilst DTT is in excess, the rate of DTT oxidation
192 is proportional to the concentration of redox-active species in the PM (Cho et al., 2005; Sauvain et al., 2008).
193 The DTT loss over time can then be expressed per unit concentration of PM (usually μg) or by volume of air
194 (m^3) to provide a measure of the intrinsic reactivity of the particles and assess human exposure (Cho et al.,
195 2005), respectively.

196 A review of the pioneer DTT assay protocols revealed differences, and therefore to derive a simplified protocol,
197 some variations of the parameters were examined by the ILC organiser laboratory. These results were
198 evaluated by the RI-URBANS core group to obtain the final harmonized protocol.

199 Three key parameters were tested. First, the necessity for the inclusion of trichloroacetic acid (TCA) was
200 evaluated. In the original DTT protocol by Kumagai et al. (2002), the reaction between samples and DTT is
201 quenched at a specified incubation time by the addition of 1.0 ml of 10% TCA to the incubation mixture.
202 Subsequently, 0.5 ml of the reaction mixture is extracted and combined with DTNB and tris–HCl buffer (pH 8.9).
203 However, more recently, Li et al. (2009) demonstrated that DTNB rapidly reacts with DTT, with the absorption
204 reaching its maximum value immediately and remaining stable for over two hours. In our initial tests, we found
205 that this parameter was consistent showing no differences over all the samples tested with or without TCA
206 (Figure S1). Thus, in the simplified OP RI-URBANS SOP, TCA addition was omitted, and we introduced the DTNB
207 solution directly into the mixture at the prescribed incubation times and recorded the absorption after the 30-
208 minute reaction.

209 Second, EDTA is present in some OP DTT protocols, whether in the buffer of the incubating PM sample with
210 DTT (Kumagai et al., 2002; Li et al., 2009), or in the titration mixture of DTNB (Cho et al., 2005; Kumagai et al.,
211 2002). EDTA is a strong chelating agent which is widely used in biological assays to prevent microbial
212 contamination and to facilitate cell lysis and the extraction of cellular components. Using EDTA is helpful in
213 purifying buffers at a low cost and decreasing a high rate of DTT loss in the blank by scavenging metal ions.
214 However, it can lead to artefacts during the assay. This is especially critical when used in the reaction mixture
215 with the PM, where it could induce complexation with redox changes. Moreover, this is particularly relevant for
216 iron where complexation increases solubility and the resultant EDTA-Fe complex is redox-active (Gao et al.,
217 2024), or in the opposite, EDTA can chelate some metallic species, preventing their reactivity (Charrier and
218 Anastasio, 2012). In addition, EDTA also has antioxidant properties, which may compete in the solution with
219 DTT (Thbayh et al., 2023). Our results on different samples show that the presence of EDTA in the buffer leads
220 to underestimation of the OP DTT loss rates in comparison to without EDTA. An impact was observed in the
221 solutions, mainly the copper reference solution (1 µM) and an ambient PM filter for testing both protocols
222 (Figure S2). That augmentation could also be related to an increase in the blank absorbance without EDTA due
223 to the impurities in the buffer, but this is controlled by subtracting the blank. Little or no impact was shown on
224 the 1,4-naphthoquinone solutions, an organic component. To prevent such undesirable interactions, many
225 laboratories have introduced Chelex® 100, a sodium-form resin to purify the buffers used in the OP DTT assay
226 (Calas et al., 2017, 2018; Charrier et al., 2015; Charrier and Anastasio, 2012), or used commercially available
227 high-purity (e.g. LC-MS/MS grade) water and buffer mixture to create the OP reaction medium (Shahpoury et
228 al., 2019, 2022). Nevertheless, the Chelex® commercial resin comes with a basic pH and requires a pre-
229 treatment that could be an extra source of error for this current first international intercomparison. Finally,
230 EDTA was not included in the SOP to prevent complex ligand chemistries, and because the use of Chelex® was
231 complex to introduce for such first ICL; high-grade buffer powders were sent to all the participants instead.

232 Third, original protocols include the use of a Tris-HCl buffer at pH 8.9 in the solution of titration with DTNB,
233 and this remains widely used. However, Li et al. (2009) showed that the pH of the solution drives both the
234 catalytic redox reaction rate and also the molar extinction coefficient of the product of the reaction, TNB. This
235 report confirmed the previously obtained results by Danehy et al. (1971) that showed that DTNB suffers from
236 alkaline decomposition above pH 8, increasing absorbance values (Figure S3). As a result, for the simplified RI-
237 URBANS DTT SOP, the core group selected a potassium phosphate buffer at a physiological pH of 7.4 to replace
238 tris-HCl in the DTNB solution. This prevents the DTNB alkaline decomposition because the pH is in the
239 favourable range of 5.5-8 where TNB is in the TNB^{2-} form and the DTT+DTNB system does not show significant
240 pH-dependant changes in the absorbance values (Li et al., 2009).

241 Finally, the simplified RI-URBANS DTT SOP also includes a variation considering the instrument used for the
242 measurements. The SOP was elaborated and tested for both cuvette and plate reader spectrophotometers,

243 including the potential application of automatic samplers. However, the simplified SOP remains to be tested for

244 other instruments (such as Liquid waveguide capillary cell instrument (LWCC)).

245

246 **2.2 Simplified RI-URBANS DTT SOP and other measurements**

247 The simplified RI-URBANS DTT SOP is proposed in SI-1. It contains a first step for the preparation of the

248 reagents needed for the analyses included in the ILC. A second step describes how to perform a calibration of

249 the analytical device, using a DTT calibration curve with at least 4 points for a concentration range between 0

250 and 60 µM (titration with 1mM DTNB and reading of TNB formation at 412 nm). In the third step, the SOP

251 defines the performance of the measurements for the test samples provided, including the assessment in

252 triplicates of each test sample and control points (blanks). It should be noted that the DTT protocol also

253 integrates the analysis of control points (blanks), which allows quantifying the inherent DTT background

254 oxidation.

255 The duration of the analyses required for the ILC is variable depending on the instrument used. About 30 min

256 completion time is required, including the assessment of ILC test samples and control points, when performed

257 with a plate reader, and a similar time is needed to perform the calibration curve. When a cuvette-type

258 spectrometer is used, the total analysis time can be at least 2 hours to perform all the triplicates and the

259 corresponding calibration curve.

260 Furthermore, apart from the analytical equipment for monitoring the chemical reactions, the simplified

261 protocol also requires some standard laboratory equipment and conditions, such as access to ultrapure water

262 (18.2 Mohm cm^{-1}, TOC <5 ppb) for the preparation of reagents, the use of vortex for the homogenisation of

263 samples, refrigerated baths to conserve the reagents and transparent 96-wells plates and dark tubes. The

264 samples also need to be kept under agitation during the experiment and at a constant temperature of 37.4°C.

265 The calculation of the chemical reaction rate of OP DTT during this ILC involves a conversion using a calibration

266 curve. Once the results are obtained, the kinetics of the DTT oxidation can be calculated by subtracting both the

267 intrinsic absorption of each sample (absorption obtained from the samples before the addition of reagents to

268 remove a potential matrix effect between samples) and the inherent DTT auto-oxidation rate (slope of a Control

269 sample) from the DTT consumption rate in the presence of PM.

270 Participants were asked to perform additional OP measurements on the same samples, following the protocol

271 in use in their laboratory ("home protocol(s)") if they wanted to do so. In this case, they had to provide the

272 results in the particular units requested, depending on the applied assay.

273

2.3 Type of samples – test materials

The ILC was performed using three samples (SP1-SP3), including different concentrations of ambient PM and commercial positive control (1,4-naphthoquinone, CAS [130-15-4], Sigma Aldrich), all extracted in ultra-pure water and prepared by the ILC organiser. Providing ultra-pure water extracts - instead of filter fragments - to the participants was selected for the current first ILC to avoid additional uncertainties associated with the use of different procedures of sample extraction, different quality of the ultra-pure water for sample extractions, and changes linked to the processing equipment available. More specifically, the samples sent to the participants included SP1: 1,4-naphthoquinone solution (reference compound, 5 µg mL^{-1}), SP2: extract from a PM sample influenced by biomass burning emission (obtained from a chamber experiment, at 25 µg mL^{-1}), and SP3: an urban PM extract highly influenced by traffic emission (from pooled roadside samples obtained from TEOM - FDMS reference samplers, at 25 µg mL^{-1}). Additionally, a fourth sample, SP4: a sample extracted from a blank/clean quartz filter was sent to the participants, but it was not included in the evaluation since the measured values were close to the instrument limits of detection for most participants. For each of the 4 samples, all the sub-samples, distributed to participants, resulted from a unique 1L solution obtained from the original sample substrate. For instance, SP1 and SP3 were powder and concentrated extraction, respectively, that were solubilised and homogenised for 75 min by vortex agitation in ultra-pure water. SP2 and SP4 were quartz fibre filters subjected to a 75-minute vortex extraction in ultrapure water.

Several 5 ml sample aliquots in dark polypropylene tubes were sent to each participant, according to their needs, allowing them to perform triplicate measurements for the RI-URBANS DTT SOP and all the "home" OP protocols implemented in their labs.

Solid potassium dihydrogen phosphate (CAS [7778-77-0], Roth), di-potassium hydrogen phosphate (CAS [7758-11-4], Roth), 5,5'-Dithio-bis-(2-nitrobenzoic acid, CAS [69-78-3], Roth) and 1,4-Dithiothreitol (CAS [3483-12-3], Roth) were also distributed to the participants, to prepare the solutions for the RI-URBANS DTT SOP, including the DTT solution, the Dithio-bis-(2-nitrobenzoic acid) (DTNB) solution, and the potassium phosphate buffer solution.

2.4 Transport of samples, ILC performance and duration

Test samples (SP1-SP4) were shipped to all participants on 17th January 2023 via courier in refrigerated and isolated ice packs, and received as chilled liquid samples. The parcels were delivered between 18th January and 2nd February 2023. On average, the participants received the samples in 3±2.5 days and performed the analysis in 14±10.5 days and up to 31 days after reception of samples. The recording of these parameters allows their integration to the multiple linear models used in this work.

2.5 Reporting of the results

Participants were asked to report OP DTT results from the RI-URBANS SOP in nmol DTT min^{-1} µg^{-1} and the % DTT consumed in µg^{-1} min^{-1}, applying three decimal digits for all three replicates of test samples. An Excel spreadsheet with all the calculations pre-included was prepared by the ILC organiser and shared with all the

9

309 participants to avoid calculation errors and to facilitate the standardisation of results. In addition, participants
310 were invited to report, under the same format, the values for other OP tests, such as OP DTT "home", and other
311 OP tests like AA, DCFH, OH, ESPR, GSH and RP (routinely applied by each participant) on the same samples.

312 **2.6 Number of participants**

313 It is worth noting that for the first time, a total of 20 research groups participated in the exercise: 14 of them
314 from Europe, including the United Kingdom, Italy, France, Switzerland, Greece, Germany, Serbia, the Czech
315 Republic, the Netherlands and Sweden, 3 participants from the United States, 2 participants from Canada and
316 1 from Australia. The participants were invited for their contribution to the RI-URBANS project, through a
317 public call to participate, or because they contacted the ILC organiser directly and were selected, due to their
318 active role in the OP scientific community. The ILC was performed using anonymous participation; thus, a
319 number was randomly assigned to each participant to present the results. Participant L5 cancelled his
320 participation in the ILC and two participants (L3 and L16) did not send their results for RI-URBANS DTT SOP.

321 **2.7 Data evaluation**

322 The ILC results were analysed by the European Commission Joint Research Centre (JRC), which provides
323 independent, evidence-based science and knowledge support for EU policies and in conducting ILC exercises.
324 The participation of an external independent evaluation was required following the International Global
325 Standard ISO 5725-2, related to the accuracy of measurement methods and results (Part 2: Basic method for
326 the determination of repeatability and reproducibility of a standard measurement method). The data
327 evaluation includes the assessment of the test sample homogeneity and stability, of each laboratory
328 repeatability, and participants' performance.

329 **2.7.1 Estimation of the assigned value and participant performance**

330 Participant performance is evaluated based on biases against pre-assigned criteria including the assigned
331 values and standard deviations for proficiency test.

332 The choice of the methods for determining these assigned values and standard deviations is under the
333 responsibility of the ILC organiser. The standard uncertainty of the assigned value shall be as small as
334 possible to minimize the risk that participants will receive underperformance signals because of inaccuracy
335 in the determination of the assigned value. Three methods including the use of (i) a simple mean and standard
336 deviation including all participants, (ii) the Q/Hampel test, and (iii) the consensus value and standard deviation
337 from expert laboratories were compared.

338 Six participants (L2, L4, L8, L12, L13 and L19) were selected a priori (without knowing their results) as expert
339 laboratories based on their previous pioneering experience in developing OP measurement protocols and their
340 strong expertise (i.e. >10 publications) in the field. The "consensus among expert laboratories" approach was
341 selected for determining the assigned values (X = 0.53, 0.14, 0.07 nmol min^{-1} μg^{-1} for SP1, SP2 and SP3,

342 respectively) and standard deviations (σ^* = 0.16, 0.06, 0.04 nmol min^{-1} µg^{-1} for SP1, SP2 and SP3, respectively)

343 for proficiency test because it led to the smallest relative uncertainties for the assigned values, ranging from

344 10% to 13 % for test samples SP1 to SP3.

345 The performance of each participant was further evaluated using z-scores, a metric indicating the deviation of

346 each data point from the assigned value as compared with the standard deviation for proficiency assessment, *z*

347 *= (x_i-X)/ σ^*,* where x_i is the result from participant *i.* An "action signal" is triggered if a participant's entry

348 produces a z-score exceeding +3 z or falling below -3 z, indicating a deviation of more than 3 standard

349 deviations from the assigned value. Similarly, a "warning signal" is raised for a participant z-score above +2 z

350 or below -2 z, representing a deviation between 2 and 3 standard deviations. A participant z-score between -2

351 z and +2 z signifies satisfactory performance concerning the standard deviation for proficiency assessment.

352

353 **2.7.2 Analysis of the variability of the results**

354 Additionally, the statistical distribution of results was evaluated using multiple linear regression models. In the

355 first model, the effects of the protocol variables on the measured OP were investigated using linear regression

356 models adjusted on the instrument (3-class variables: plate reader, cuvette and LWCC), delivery time (time

357 between sample shipment and reception, continuous), and analysis time (time between reception and analysis,

358 continuous). An additional model (M2) compared the RI-URBANS SOP and the DTT-home protocols was further

359 adjusted based on the protocol (2-class variable: RI-Urbans, DTT-home). Finally, the evaluation of the average

360 performances (3-class variables: low - 0<|z-score |<2, middle - 2<|z-score |<3, and high - |z-score |>3) was

361 added in the M2 model, to assess whether performance affected DTT activity in the same direction (i.e. positive

362 or negative), while considering other protocol variables. Each model was run separately for SP1, SP2 and SP3

363 samples. All analyses were conducted using R (version 4.2).

364

365 **3. Results and Discussion**

366 Out of the group with a total of 20 participants, 18 presented results obtained using the RI-URBANS DTT SOP.

367 Different instruments were used to apply the simplified SOP. Overall, 9 participants (47.5%) used the cuvette-

368 type spectrophotometer, 8 (42%) used the plate reader-type spectrometer, and 2 (10.5%) implemented LWCC

369 measurements (one participant used two instruments).

370 **3.1 Homogeneity of the samples**

371 An initial assessment of the homogeneity of the OP measurements with the 3 test samples was performed by

372 the ILC organiser, using a plate-reader type protocol, deriving the mean and the standard deviation of 10

373 replicate analyses performed on the same day. The results obtained from the coefficient of variations, showed

374 the sample variabilities were up to 12%, 7%, and 9% for SP1, SP2 and SP3, respectively (Figure S5), showing a
375 higher variability for the 1,4-naphthoquinone solution (SP1) compared to the two filter extracts (SP2 and SP3).

376 The overall uncertainty of the OP DTT assay has been evaluated to 18% for PM_{10} and 16.3% for $PM_{2.5}$ by Molina
377 et al., 2020. Despite some differences observed between our samples, the results are deemed acceptable,
378 presenting a variability of around 10%, which indicates a very good performance of the analysis.

3.2 Ageing of samples

380 To reduce the number of parameters affecting the preparation of the sample solutions, liquid solutions of each
381 sample were prepared and sent to the different participants. However, liquid samples can undergo ageing
382 processes, impacting OP levels over time. For this purpose, an ageing test was performed by the ILC organiser
383 to evaluate the potential changes over time. It consisted of regularly implementing the RI-URBANS DTT SOP to
384 obtain the values of each test sample over time. Figure S6 shows these results, where SP2 and SP3 do not show
385 a strong change over time, while sample SP1 presents a pronounced ageing effect. In routine tests of ICL
386 organizer, the 1,4-naphthoquinone mother solution at such high concentration is usually stable in a glass
387 container for weeks but here, potential interaction with the PP tubes' inner surface may have happened.
388 Consequently, ageing could be a variable of importance for the participants who analysed the samples toward
389 the end of the required period, and such parameter (date of analysis) was thus included in the parameters to
390 be tested for the research of critical parameters.

391

3.3 Statistical distribution of results: Participants' variability

393 In order to assess the intra-laboratory variability of the results, the coefficient of variation (COV = standard
394 deviation/ mean * 100) of the results for each sample and each laboratory are presented in Figure 1, while the
395 standard deviations of the replicates reported for each sample are presented in Figure S7 and table S1. Overall,
396 higher COVs are observed for SP3 and SP1, where most participants (44.4 and 38.9%, respectively) presented
397 higher values for this sample compared to the SP2 sample. Specifically, high average COV values are observed
398 by L1, L12, L14, L15 and L21, with an average variation higher than 40%. Only a few participants (6 groups)
399 presented a variation lower than 10% for the three samples. This is the same pattern for the results obtained
400 by the ILC organiser during the homogeneity test (see 3.1.), where the COV for SP1 was larger than those for
401 SP2 and SP3 but with the highest COV below 15%. These findings confirm more homogenous results for
402 samples SP2 and SP3 compared to SP1 but could also indicate that some participants failed to achieve
403 repeatability observed by the ILC organiser. However, some groups (L2, L10, L19, L20) were able to produce
404 very homogeneous results with COV < 10% for all 3 samples.

405
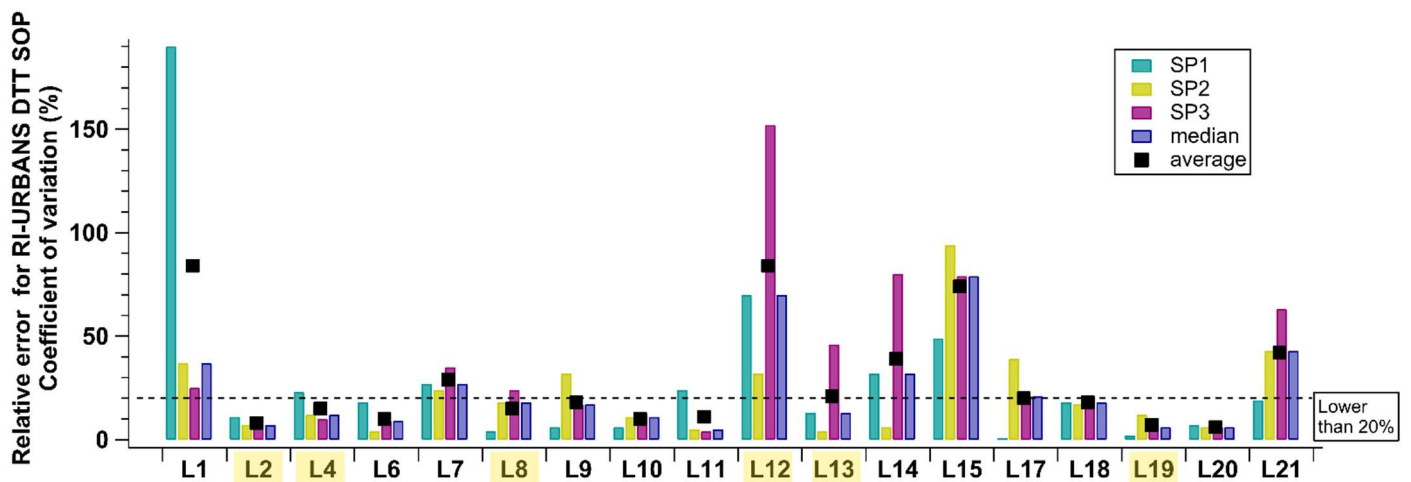
Figure 1: Coefficients of variation of each participant (L1 to L21) for the three samples in triplicates tested using the RI-URBANS DTT protocol and the median and mean repeatability for each laboratory. Yellow-highlighted participants are the ones selected for the calculation of the assigned values. The dashed line indicates the participant with COV lower than 20%.

410

3.4 Laboratory performances

The assessment of laboratory performances first presents the bias in results across participant groups compared to the assigned values and their associated standard deviation for each sample. As illustrated in Figure 2, SP1 exhibited the highest variances, ranging from 130% to -35%, with only five groups displaying differences within ±10%. The distribution of results for SP1 indicated a mix of overestimations and underestimations. For SP2, differences are within a narrower range from 43% to -7%, primarily favouring overestimations. For this sample, 12 participants returned results that were within ±10% of the assigned value (see highlighted laboratory numbers in Figure 2). Finally, the results for SP3 demonstrated the least variation among participants, with differences ranging from 30% to -6%, and 16 participants within ±10% of the assigned value, again favouring overestimation compared to the assigned value. In total, 14 laboratories obtained data with ±10% difference to the assigned value for SP2 and SP3 (see highlighted laboratory numbers in Figure 2). These results show again that the reference samples with 1,4-naphthoquinone (SP1) most probably present some characteristics leading to this variability and may be associated with a less stable solution or led to saturation of some detectors regarding the relatively high concentrations, while the samples from filter extractions do not. Additionally, it is interesting to note that there is apparently no systematic pattern where a given participant would obtain out-of-range results for all samples. The results are really diverse, and most participants can obtain "acceptable" results for one or two samples (SP) and larger variability associated with one "unacceptable result" for one of them. In 2020, Molina et al. (2020) explored the total uncertainty of OP DTT of a collection of samples and evaluated it to 18% for PM10 and 16.3% for PM2.5. The

13

430 leading factors identified were the DTT consumption rate (regression and repeatability of experimental data)
431 and the extraction volume operations (pipette). This underscores the need for further investigations on the
432 experimental causes of the variations observed, possibly in the next ICL.
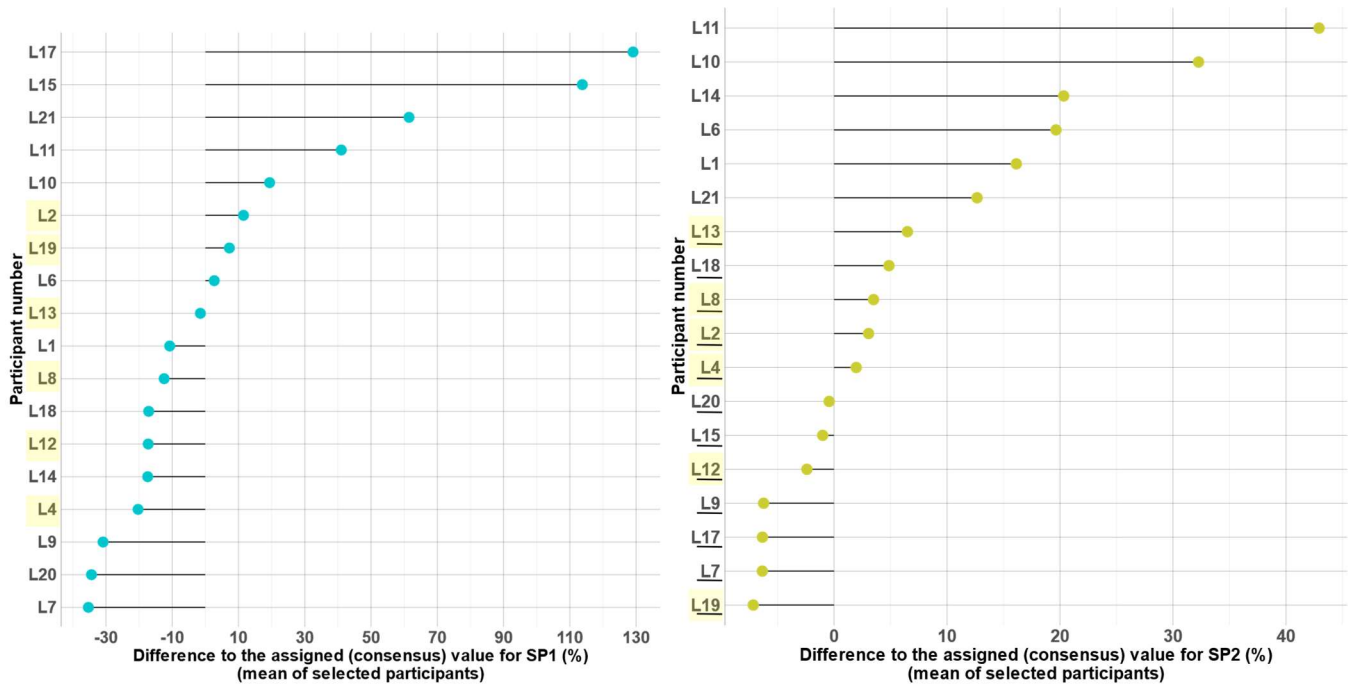
433
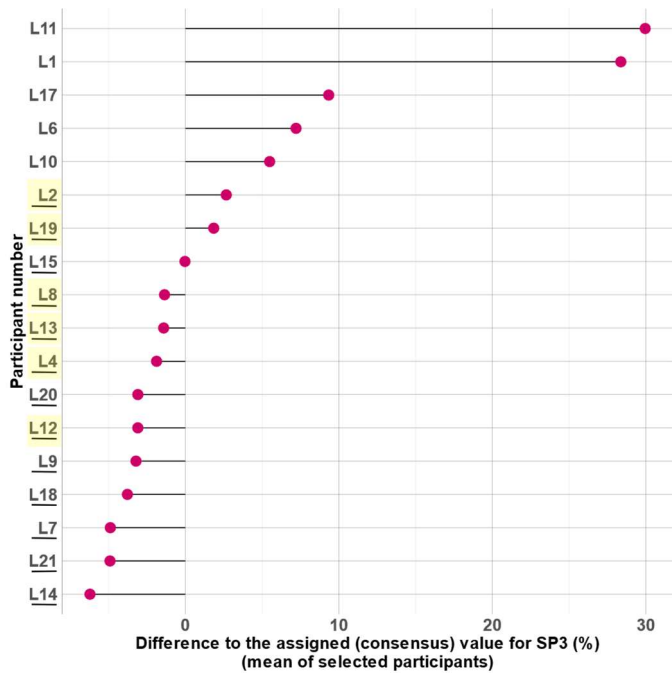
434

435 **Figure 2. Percentage differences from the assigned (consensus) value for each sample (SP1, SP2 and**
436 **SP3). The results compared the average of the triplicates reported by the participants. Yellow-**
437 **highlighted participants are the ones selected for the calculation of the assigned values and underlined**
438 **the ones that obtained data into ±10% difference to the assigned value for SP2 and SP3.**

439

The individual performance of each group was further evaluated using z-scores. The results are presented in Figure 3. All underestimations fall within the acceptable range (lower than -2 z). Additionally, it is noteworthy that no laboratory exhibits unsatisfactory performances across all three samples; for almost all participants, while one sample can present poor results, it coexists with two acceptable ones. This has strong implications for spatial and temporal analyses that are often performed for OP. Again, this calls for attributions that there are no systematic biases in the analyses. While factors like sample inhomogeneity may be playing a role (particularly for SP1), some other issues, including variability in the performance of the analysis, may have an impact. Hence, participants exhibiting significant deviations ($|z\text{-scores}| > 2$) for some of their results should thoroughly examine their procedures and possibly implement appropriate corrective actions to avoid similar outcomes in future ILCs.

However, half of the participants achieved results within the acceptable limits of this test. Despite disparities, these findings are really promising, especially considering that this is the first intercomparison of its kind. For instance, such results are in the same range to those obtained for some of the first ILCs for PAHs (Grandesso et al., 2012; Verlhac et al., 2014).
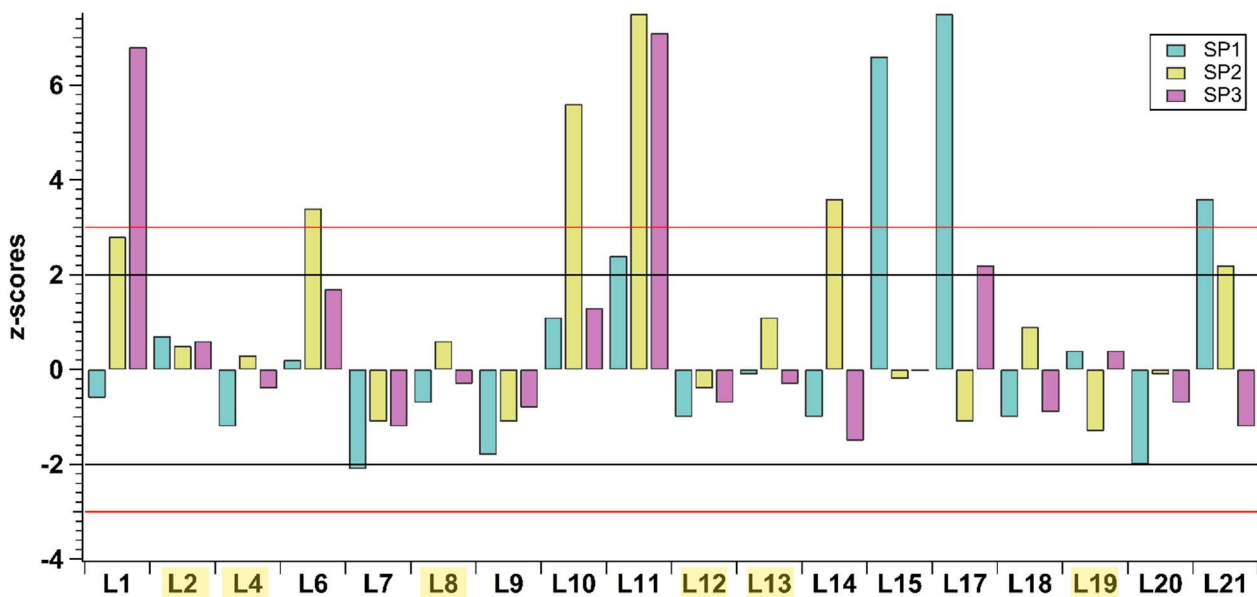

Figure 3. Z-scores were calculated to evaluate each participant's performance in the interlaboratory comparison for each sample tested. Yellow-highlighted participants are the ones selected for the calculation of the assigned values. Black and red horizontal lines indicate boundaries for triggering an action signal a described in section 2.7.1.

To gain more knowledge about the factors causing the variability of the results, we first tried to perform a cluster analysis using the Ward method. This grouped the participants into four clusters (see Figure S8), with the main cluster (in yellow) including the 10 participants encompassing mainly the ones with satisfactory Z

15

462 scores. The clustering seemed independent of the instrument used and/or the time taken between the sample
463 delivery and analysis (i.e. near the delivery time or later in February).

464 In a second step, a multiple linear regression model was run to evaluate the associations of the results obtained
465 for the 3 samples, SP1, SP2 and SP3, considering a range of parameters, including the instrument used and the
466 delivery and analysis time (Figure 4, Table 2). The beta values are shown in Figure 4, representing the
467 association (effects) between the different parameters evaluated and the OP results obtained. In the model, the
468 reference variables were the RI-URBANS DTT SOP and the results obtained with the plate-reader instrument.
469 Regarding the instrument performance, the values provided by the cuvette-spectrometer were higher than
470 those obtained with plate readers in the case of SP1 and SP2 (showing significant overestimation in the case of
471 SP2 p-values <0.05), while the results for SP3 were quite similar. In the case of LWCC, higher variability is
472 observed when compared to both cuvette and plate reader for all the samples. SP1 LWCC results presented the
473 highest variability, and SP2 results were significantly overestimated (at a 95 % confidence level) when
474 compared with those obtained by the plate reader. The RI Urbans SOP was adapted for plate readers and
475 cuvettes, in order to perform the measurements in similar conditions of concentrations for the reagents. This
476 was not the case for the LWCC since we did not have all the necessary information concerning the specific
477 devices used by participants. Figure 4 suggests that the specific conditions of the reaction are probably
478 important factors for delivering an accurate value of OP. In Figure S6, we showed that SP1's OP activity
479 decreased over time during storage, but this ageing effect was not found to be significant in the model for either
480 delivery or analysis time. The storage effect remained consistent for SP2 and SP3, as there was a clear
481 association between OP and delivery or analysis time (Figure 4).

482

483
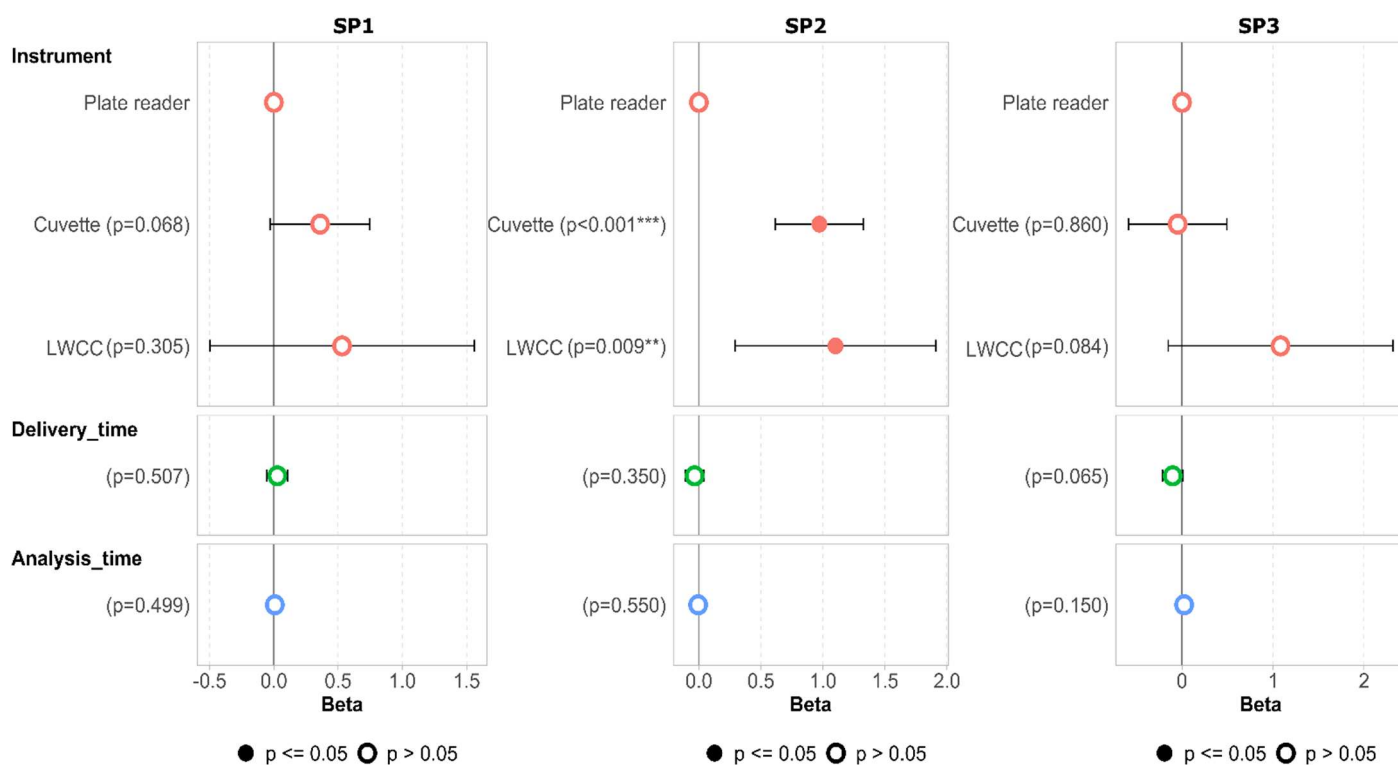
Figure 4. Associations (beta in nmol min^{-1} µg^{-1}) between OP DTT values for SP1, SP2 and SP3 using the RI-URBANS protocol and technical parameters, including the instrument used and the delivery and analysis time obtained by applying an adjusted multiple linear regression model. Full-colour dots represent the results with p-values <=0.05, and white dots represent the results with p-values >0.05.

488

489 A ranking of the samples is also proposed to evaluate the OP activity of the samples tested in this ILC and its
490 relative variability within the participants (only considering the results obtained with the simplified RI-
491 URBANS protocol). For this purpose, SP1 was arbitrarily selected as the one with the highest OP activity with
492 an assigned value of 100, and SP2 and SP3 were evaluated in function of SP1. Figure S12 shows the results
493 obtained for the relative ranking of the samples. It can be noted that most of the participants presented similar
494 relative variability with SP1 > SP2 > SP3. Some exceptions were observed for L1, L17 and L19, which obtained
495 higher ranking for SP3 than SP2. A higher variability in the relative activity is obtained for SP2 than for SP3.
496 Within the participants showing a higher relative ranking for SP2 (higher than 50% compared to SP1), most of
497 them used either cuvette-type or LWCC instruments (except L20), suggesting some overestimation in the
498 results using these instruments. Overall, this similar ranking for the samples achieved by most of the groups is
499 noticeable and very encouraging. In fact, most of the data treatment performed on OP with atmospheric
500 variables or health data relies on associations and regressions where the relative variability of a time series is
501 of utmost importance, more than the absolute value.

17

3.5 Comparison with other OP tests provided

Participants were also invited to report results obtained using other OP assays. Since not all participants submitted results from equivalent "home OP" tests, we exclusively focus on the outcomes obtained through the "DTT-home" protocols involving 13 participants (Table S3, Figure S9). It is important to note that DTT-RI-URBANS protocol was simplified and does not include EDTA, Tris-HCL, TCA neither Chelex®, whereas DTT-"home" protocols are diverse and should exhibit at least one up to 3 of the last mentioned compounds at different step of the reaction; however, this is challenging to evaluate because not all groups have submitted the protocols related to their "home" results.

We have first evaluated the COV individually from the results obtained with protocols (RI-URBANS SOP versus all DTT-"home") for each test sample. Figure 5 shows that lower COVs are generally observed in the performance of the DTT-home protocols (more details can be found in Table S3). However, six out of 12 participants presented similar COVs (within 20%) for the two protocols. These results could indicate that the use of a simplified OP protocol needs some extent of training and guidance before its application. In addition, some of the participants presented higher COV values (L1 and L13 for DTT-home) when using the LWCC instrument. The lack of a simplified protocol for this instrument did not seem to be a major issue, as the application of the DTT-home protocols was also associated with high COV.
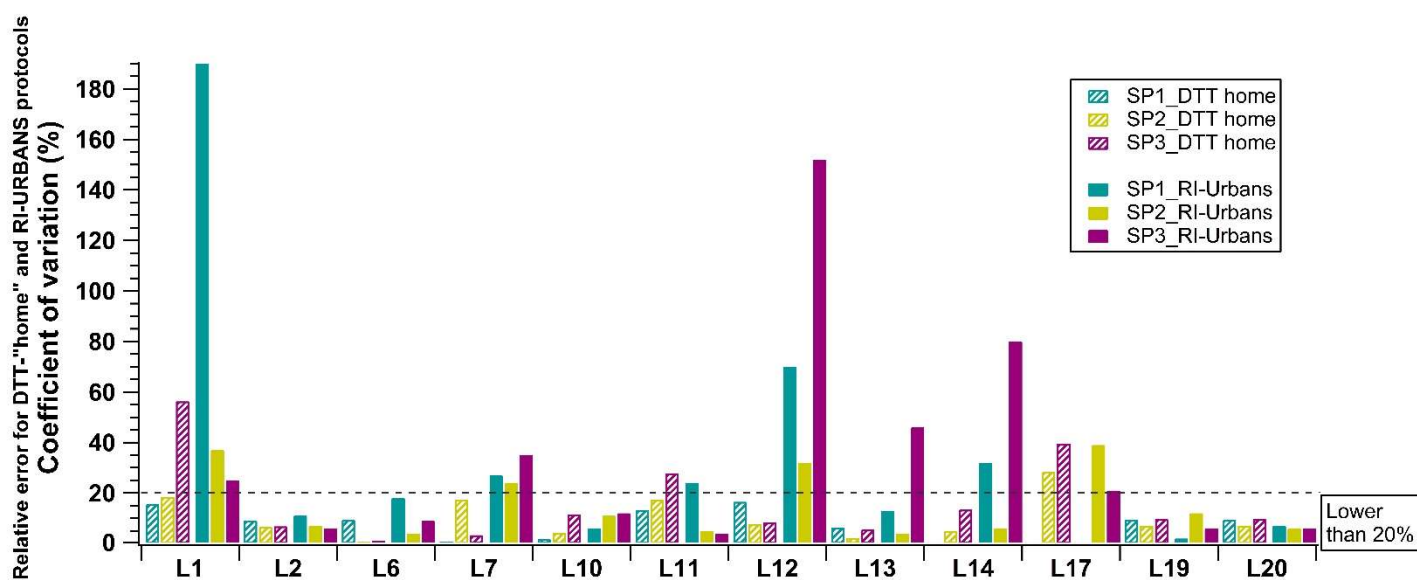

Figure 5: Coefficients of variation of each participant for the three samples tested from triplicates using both the RI-URBANS DTT and the DTT-"home" protocols. The average and standard deviation of each participant are also detailed in Table S3.

524 Another multiple linear regression model was run to evaluate the main differences in the results obtained
525 between RI Urbans SOP and DTT-"home" protocols (Figure 6). For SP1, a significant overestimation was
526 observed for the DTT-home protocol and the opposite was observed for SP3. In the case of SP2, there was no
527 statistically significant difference between both protocols. More details on the concentration of DTT for each
528 DTT method could provide more insight into this trend. Regarding the instrument performance, the LWCC
529 presents poorer results compared to the cuvette and plate reader for all the samples, which is opposite to the
530 trend observed with the results of the RI-URBANS protocol only (Figure 4). However, the results are
531 significantly underestimated for SP3 only ($p<0.05$). For the cuvette-based measurements, the results are higher
532 than those obtained with plate readers in the case of SP1 and SP2 (significantly overestimated for SP2) and
533 similar for SP3, which is in line with the direction observed with the RI-URBANS protocol only. The delivery
534 and analysis time show a statistically significant lack of effect for SP2 (analysis time) and an underestimation
535 for SP3 (delivery time) but nothing significant for SP1, although it had undergone ageing in the tests of the ILC
536 organiser. Since the effects are very small compared to the effects of the protocol, or the instrument, these two
537 variables (delivery and analysis time) may cause a greater impact on DTT values when protocols are
538 harmonised, but not to date.

539 The results obtained by the participants (the z-scores evaluation) were also added to the former model to
540 evaluate the effect on OP values while adjusting the protocol variables (Figure S10). The results show a
541 significant OP overestimation of all the samples for the labs with poor performances in SP2 and SP3 samples,
542 and also a significant underestimation in the OP value obtained for SP2 for the group with intermediate
543 performance.

544 Hierarchical cluster analysis was conducted, incorporating both the DTT "RI-Urbans" and DTT "home"
545 outcomes (Figure S11). Because some participants did not implement a DTT "home" protocol, the cluster
546 analysis involved a reduced set of OP values. The results reveal the presence of four primary clusters, with the
547 predominant cluster encompassing most participants (8 out of 12 for the DTT- "home"). The participants within
548 the green main cluster largely align with the results derived from the DTT "RI-Urbans" outcomes, encompassing
549 the groups in the two primary clusters (Figure S11). This assessment illustrates some consistency of results
550 obtained across various OP DTT protocols. Some of the participants with more reliable results for the RI-
551 URBANS DTT SOP maintain their consistency regardless of the protocol used. However, some of those that did
552 not show an acceptable performance for the simplified protocol (i.e. L1 and L10) presented a better
553 performance for the DTT-"home", and the opposite was observed for the L19 (almost for SP1).

554
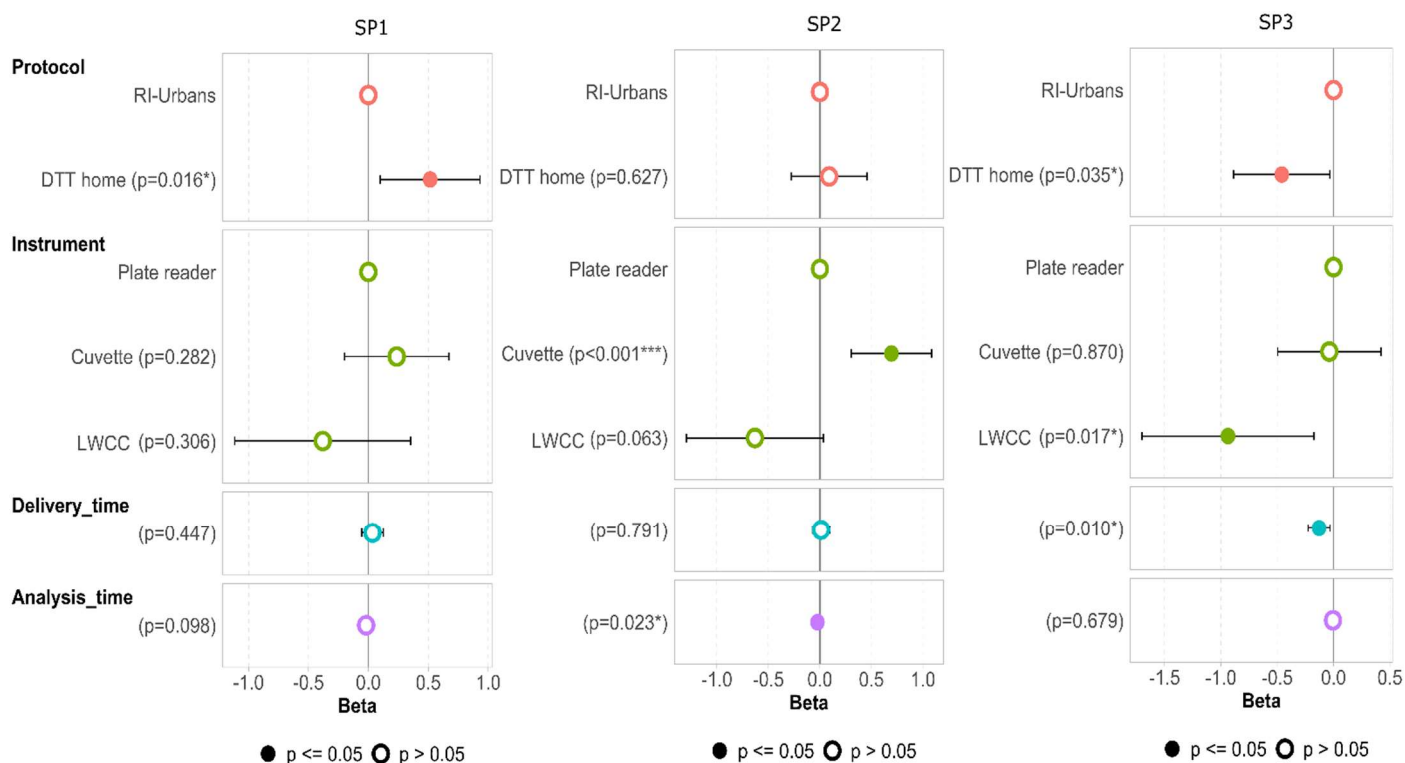
Figure 6. Associations (beta in nmol min^{-1} μg^{-1}) between OP DTT values obtained for SP1, SP2 and SP3 and the different parameters of the ILC, including the DTT protocol, the instrument used and the delivery and analysis time obtained by applying a multiple linear model. Full-colour dots represent the results with p-values <=0.05, and white dots represent the results with p-values >0.05.

559

Finally, to assess the performance of the participants in the DTT-"home" protocols, a comparable approach to the simplified RI_URBANS SOP was employed for those participants who supplied OP results. The z-scores were computed using the assigned values of each sample (SP1-SP3), obtained with RI-URBANS SOP application. Figure 7 illustrates the z-scores of the OP results obtained through the application of the DTT-"home" protocols, revealing a significant variation in the outcomes. Only five participants managed to produce satisfactory results for all the tested samples. Despite the fact that the COV of the participants using DTT-"home" protocols showed an improvement over the results of the simplified DTT SOP (Figure 5), the outcomes are still distant from the consensus values of the samples obtained in this exercise. The results indicate a high degree of variability in the OP activity using "home" OP methodologies, underscoring the pressing requirement for standardized methods and harmonised protocols to ensure more reliable OP research.

570
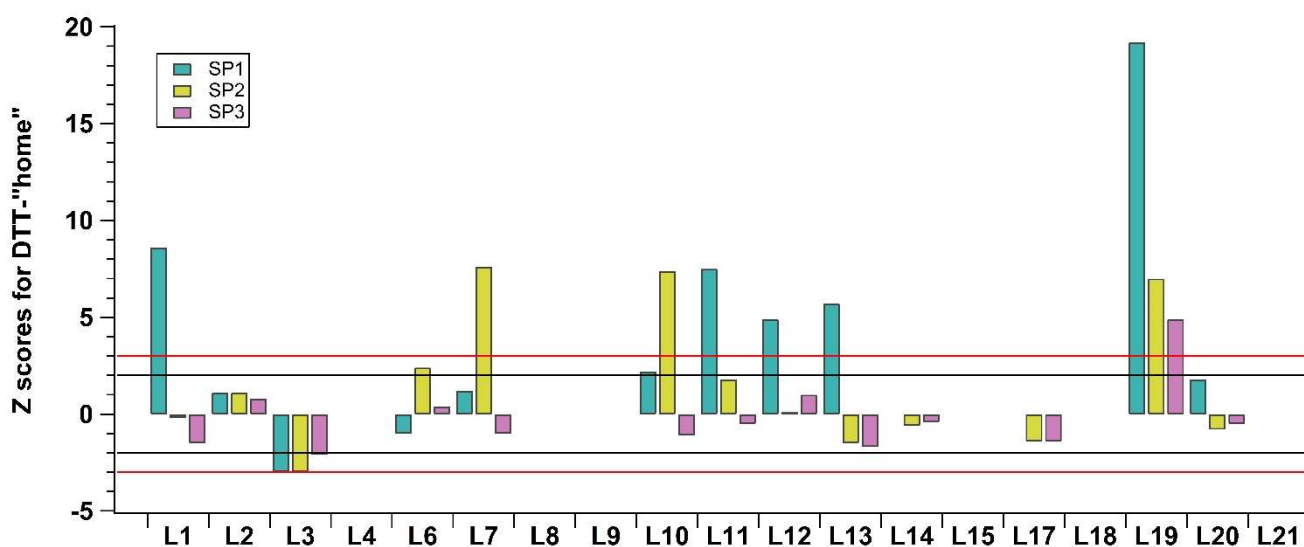
Figure 7. Z-scores were calculated for the DTT-"home" protocol results to evaluate each participant's performance in reference to the RI_URBANS assigned (consensus) values, for each sample tested. Black and red horizontal lines indicate boundaries for triggering an action signal a described in section 2.7.1.

4. Strengths and limitations of this first intercomparison

The greatest strength of this ILC was the high number of participants (20) enhancing the comprehensiveness and diversity of the study and allowing for a broader range of perspectives and expertise. This also allowed comprehensive collaborative discussions during the preparation phase, promoting knowledge exchange and consensus-building, and contributing to a more robust ILC design. These all show a willingness from the groups to be actively part of the development of the intercomparison and to pursue a harmonisation on the OP measurements.

The development of the first simplified OP DTT protocol (available in SI-1) also consolidates the experimental experience of the participants, fostering methodological consistency across different research groups as a first step toward method harmonisation. Finally, the collaboration with the JRC, an independent organisation for the assessment of results, adds credibility and objectivity to the study, ensuring that findings are impartially evaluated.

The sharing of liquid samples in this comparison comes with both advantages and limitations. On one hand, it eliminates biases associated with extraction methods and solvent purity. However, some samples exhibited signs of ageing during the interlaboratory comparison duration (though this was not identified as a critical parameter when identifying the main causes of variability). In addition, this approach introduced certain challenges with some of the "home" OP protocols which were designed originally to be used with solid samples.

21

593 Finally, all liquid extracts should be provided with a similar PM concentration to limit known nonlinearities and
594 to avoid potential saturation issues, as can be the case of LWCC instruments. Next, ICL should, in the future,
595 include the whole chain assessment, including the extraction step.

596 The testing of three samples with different patterns makes it difficult to draw unilateral conclusions. A larger
597 sample size could support a more robust statistical analysis of the results, particularly for the factors
598 determining OP variability. Moreover, the inclusion of samples that are readily accessible worldwide, such as
599 standard reference materials, could facilitate the future adaptation of a simplified OP DTT protocol while
600 allowing comparison with an assigned (consensus) value.

601 The sole focus on the DTT method for the ILC could limit the broader evaluation of OP. The addition of other
602 OP assays, such as those included in previous inter-comparison studies (Ayres et al., 2008; Calas et al., 2018;
603 Shahpoury et al., 2022) could provide a more comprehensive understanding of the performances of the
604 different groups involved in the OP domain of research. There are contrasting reports about the relative
605 sensitivity of DTT assay to various organic and inorganic PM components, with some studies showing higher
606 reactivity towards the organic fraction. Therefore, additional consensus studies would be needed to assess this
607 aspect and the comparability of DTT to other OP metrics that rely on proper lung anti-oxidants and could be
608 considered more physiologically relevant. Such studies could support the identification of chemical species
609 which should be prioritized for future air quality management programs.

610 In conclusion, while this ILC of OP has highlighted considerable variability in the performance of the assay
611 between groups, it has notable strengths and provides a starting point towards the harmonisation of OP
612 measurements.

613

614 5. Recommendations for standardisation of OP protocols

615 Based on the findings of this ILC and also on general literature about OP, some recommendations for further
616 standardising OP DTT measurements are proposed (Table 1). These include guidelines for sample and
617 laboratory conditions, instrument type and calibration and the reporting of results. Additionally, a reference
618 material (1,4-naphthoquinone, copper or other solution at a known concentration) should be proposed to
619 facilitate future ILCs. Additionally, since some differences were observed in the results obtained from the use
620 of the simplified SOP compared with the "home-developed" DTT protocols, harmonisation of procedures is
621 needed to ensure data comparability. We describe below the crucial parameters that need to be considered in
622 the move toward greater harmonisation of OP methodologies.

623 *OP assay selection*

624 •   To date, it remains unclear which oxidative potential (OP) assay is most effective at predicting health
625 outcomes related to oxidative stress. This uncertainty arises because different assays yield markedly different

626 results for the same particulate matter (PM) samples. Additionally, even OP values from the same assay are
627 often linked to various PM components and sources, depending on the different studies (He and Zhang, 2022).
628 Thus, based on current knowledge and epidemiological evidence, two complementary OP assays (a thiol-
629 based probe (OPDTT or OPGSH) and another one (among OPOH, OPAA, or else)) are recommended to provide
630 a better picture of the potential oxidising damages from PM compounds and to strengthen the power of
631 epidemiological studies. These aspects were previously discussed in a recent work integrating five different
632 OP assays (Dominutti et al., 2023). Finally, the final choice of the best OP test (or combination) must be based
633 on epidemiological evidence, which has begun only recently and needs more hindsight to be determined.

634 *Sampling*

635 • OP can be analysed in filter samples conventionally collected for air quality monitoring using small
636 portions of these if adequately preserved (frozen). Pre-burn quartz filters or Teflon filters are appropriate
637 and blank filters must be measured to remove the background induced by the matrix of the material. A
638 previous study had shown no differences in the OPDTT values observed using Quartz or Teflon filters
639 (Frezzini et al., 2022). However, it should be further evaluated when other OP assays are considered.

640 *Sample storage*

641 • Previous studies that evaluated the effect of storage time and conditions did not show a substantial effect
642 on the OP DTT results (Frezzini et al., 2022). However, we recommend that PM samples should be
643 immediately transported to the lab after sampling. The filters must be kept cold after sampling (at 4°C if the
644 OP analysis is done within a few days after collection or -20°C if the analysis is delayed).

645 • The lifetime of the ROS may be very short, and measurements of OP on PM-extracted filters are likely
646 affected both by the age of the samples, how they have been sampled and stored, and the nature of the
647 extraction methodology. How all of these processes impact on the ageing of samples and the ultimate
648 quantification of OP needs to be addressed. Ageing studies should be performed for each OP assay in the long
649 term to define the maximum storage time of aerosol filters at low vs ambient temperature conditions.
650 Some OP components might be so short-lived that only online techniques are warranted.

651 *Laboratory conditions*

652 • OP assays are "trace" detection assays that require clean ambient conditions and high-quality reagents
653 free of metal contamination. Considerations should be given to the use of certified clean rooms or proper
654 laminar flow bench stations to prevent contamination of the samples.

655 • Use of clean material: vials, cones, and spatulas have to be washed before use (5% HNO3 bath to remove
656 metals and rinse three times in ultra-pure water before drying in laminar flow).

657 • Control laboratory temperatures and light exposure by using dark polypropylene tubes at least for
658 reactants

Extraction step

659

660 • The extraction step may be highly variable according to the procedures used, and several parameters are
661 known to impact OP results, such as the choice of the solvent, the concentration of buffer, the way of agitation,
662 and the quantification of the final extracted mass. Notably, the ultrasonication of PM samples in aqueous
663 solutions generates ROS (Miljevic et al., 2014) and it could introduce artefacts in OP measurement. This effect
664 was also observed in the work of Frezzini et al. (2022), where different extraction methods were evaluated,
665 with ultrasonic baths overestimating the results observed.
666 The effect of the solvent used was not evaluated in this ILC exercise. However, we recommend the use of
667 ultrapure water or simulated lining fluid for the sample extraction. Future ILC exercises should include the
668 evaluation on the extraction conditions, including solvent use and methods.

669 *Reaction step*

670 • Several aspects in the reaction process affect the OP value, like the initial concentration of reactants (since
671 the DTT test is mass-dependant (Charrier et al., 2016)), ratio of reactant/sample, time of reaction (some
672 compounds present a non-linear reaction over time), the temperature of the reaction (which should be
673 standardised to 37°C), agitation (mixing samples) and the type of measurements (kinetic or end-point value),
674 etc.
675 • Current literature mainly addresses extraction or reaction parameters separately. We advise that the
676 whole chain factors should be evaluated together to quantify their relative impact on the results.

677 *Development of a reference material with a certified "OP value."*

678 The setup of reference material or in-house standard solutions (in collaboration with reference institutions
679 JRC or NIST, for instance) with a known OP value could help laboratories test and train themselves on the OP
680 protocol before testing the unknown ILC samples. This is something to be developed and tested in future ILCs.

681 *Instrument calibration*

682 • Investigate the optimal frequency for the calibration of spectrophotometers for such assays.

683 *Report of results/units*

684 The calculation of OP DTT activity during this ILC involved a conversion using a calibration curve. Since the
685 OP activity measures the rate of a chemical reaction and not a concentration, for future comparison exercises,
686 the possibility of exploring alternative methods for OP calculation should be tested. To date, results are mass
687 normalised in nmolAnti-oxidant min^{-1} μg^{-1}, or volume normalised in nmolAnti-oxidant min^{-1} m^{-3}. The OP per
688 μg refers to the reactivity of one μg of the tested PM, whereas the OP per m^3 refers to the exposure of one m^3
689 of inhaled air.

690 Table1. Summary of recommendations for future OP measurements on filters

Condition or step	Recommendations
OP assay selection	• Two complementary OP assays (a thiol-based probe (OPDTT or OPGSH) and another one (among OPOH, OPAA, or else)) are recommended to provide a better picture of the potential oxidising damages from PM compounds
Sampling	• Pre-burn quartz filters or Teflon filters are appropriate and blank filters must be measured to remove the background induced by the matrix of the material.
Samples storage	• The PM filters must be kept cold after sampling (at 4°C if the OP analysis is done within a few days after collection or -18°C or -20°C if the analysis is delayed).
Laboratory conditions	• Clean conditions (including certified clean rooms or proper laminar flow bench stations) • High-quality reagents free of metal contamination • Use of clean material, which must be washed before use (5% HNO_3 bath to remove metals, rinse three times in ultra-pure water, and dry in laminar flow bench stations). • Control laboratory temperatures and light exposure by using dark polypropylene tubes
Reaction step	• Several aspects in the reaction process affect the OP value, and to minimise their impact, standard conditions should be fixed as the initial concentration of reactants, ratio of reactant/sample, time of reaction, the temperature of the reaction (37°C), agitation (mixing samples) and the type of measurements (kinetic or end-point value), etc.
Instrument calibration	• Investigate the optimal frequency for the calibration of spectrophotometers for such assays.

691

6. Conclusions

693 This study represents an innovative effort as the first interlaboratory OP exercise specifically aimed at
694 harmonising this OP assay. This exercise provides the very first roadmap for refining interlaboratory
695 comparisons of OP, fostering greater confidence in the reliability of OP data and encouraging the scientific
696 community to advance towards global OP harmonisation.

697 This first exercise focused on OP DTT, as it is widely used within the scientific community and has already
698 shown positive associations with health outcomes (Bates et al., 2015; Borlaza et al., 2022; Dabass et al., 2018;
699 Donaldson et al., 2001; Gao et al., 2020; Marsal et al., 2023; Weichenthal et al., 2016b, a, c). Even if there are
700 several crucial points to be evaluated and harmonised in the whole chain of the determination of OP (sampling
701 methods, sample storage, extraction conditions and methods) as well as the use of different OP assays, this first
702 ILC engaging several research laboratories pave the way for future developments towards the standardisation
703 of OP methods.

704 Our findings emphasise both the strengths and challenges associated with the use of the current OP DTT assay
705 for driving a measurement of PM OP. Overall, half of the participants achieved results falling within a
706 satisfactory range of z-scores for this test. The participating group performance levels are comparable to those

25

observed in initial ILCs for PAHs in the 2010s (Grandesso et al., 2012; Verlhac et al., 2014). While notable agreement was observed in certain samples and between several groups, discrepancies and variability were also identified, emphasizing the need for harmonisation in the procedures and conditions. A number of factors may contribute to the underperformance observed in certain samples and participants. The main reasons are not clear, but the analysis conditions in the participating laboratories and the lack of experience in this type of metrological exercise are possible causes. Standardisation of protocols and harmonisation of procedures emerged as critical components to ensure the accuracy and comparability of OP data across laboratories. This collaborative approach fosters a more robust OP science, facilitates data exchange and integration, and will ultimately contribute to a better understanding of the health impacts associated with PM exposure, allowing for more accurate exposure assessments and regulatory decisions.

Data availability

All OP data is published in the SI.

Author contributions

GU designed the study and supervised the OP tests for the development of the simplified DTT RI-URBANS protocol. C.R., T.M., R.E. and P.A.D. tested the different steps and prepared the samples and logistics of the intercomparison exercise. G.H., R.M.H., A.N., I. M., K. B., N.M. and G.U. evaluated and decided the samples to be compared and the protocol content. JPP and FC performed the data analysis and evaluated the performance of each group. P.A.D. and A.M. developed the multiple regression model. P.A.D. processed the data of the study and wrote the paper together with J.L.J. and G.U. before a first review by the RI-Urbans members. All authors participated in the interlaboratory comparison. All authors reviewed and edited the manuscript.

Competing interests

At least one of the (co)-authors is a member of the editorial board of Atmospheric Measurement Techniques.

7. References

Alkoussa, S., Hulo, S., Courcot, D., Billet, S., and Martin, P. J.: Extracellular vesicles as actors in the air pollution related cardiopulmonary diseases, Crit. Rev. Toxicol., 50, 402–423, https://doi.org/10.1080/10408444.2020.1763252, 2020.

Ayres, J. G., Borm, P., Cassee, F. R., Castranova, V., Donaldson, K., Ghio, A., Harrison, R. M., Hider, R., Kelly, F., Kooter, I. M., Marano, F., Maynard, R. L., Mudway, I., Nel, A., Sioutas, C., Smith, S., Baeza-Squiban, A., Cho, A., Duggan, S., and Froines, J.: Evaluating the toxicity of airborne particulate matter and nanoparticles by measuring oxidative stress potential - A workshop report and consensus statement, Inhal. Toxicol., 20, 75–99, https://doi.org/10.1080/08958370701665517, 2008.

Bates, J. T., Weber, R. J., Abrams, J., Verma, V., Fang, T., Klein, M., Strickland, M. J., Sarnat, S. E., Chang, H. H., Mulholland, J. A., Tolbert, P. E., and Russell, A. G.: Reactive Oxygen Species Generation Linked to Sources of Atmospheric Particulate Matter and Cardiorespiratory Effects, Environ. Sci. Technol., 49, 13605–13612, https://doi.org/10.1021/acs.est.5b02967, 2015.

Bates, J. T., Fang, T., Verma, V., Zeng, L., Weber, R. J., Tolbert, P. E., Abrams, J. Y., Sarnat, S. E., Klein, M., Mulholland, J. A., and Russell, A. G.: Review of Acellular Assays of Ambient Particulate Matter Oxidative Potential: Methods and Relationships with Composition, Sources, and Health Effects, Environ. Sci. Technol., 53, 4003–4019, https://doi.org/10.1021/acs.est.8b03430, 2019.

Bhattu, D., Tripathi, S. N., Bhowmik, H. S., Moschos, V., Lee, C. P., Rauber, M., Salazar, G., Abbaszade, G., Cui, T., Slowik, J. G., Vats, P., Mishra, S., Lalchandani, V., Satish, R., Rai, P., Casotto, R., Tobler, A., Kumar, V., Hao, Y., Qi, L., Khare, P., Manousakas, M. I., Wang, Q., Han, Y., Tian, J., Darfeuil, S., Minguillon, M. C., Hueglin, C., Conil, S., Rastogi, N., Srivastava, A. K., Ganguly, D., Bjelic, S., Canonaco, F., Schnelle-Kreis, J., Dominutti, P. A., Jaffrezo, J.-L., Szidat, S., Chen, Y., Cao, J., Baltensperger, U., Uzu, G., Daellenbach, K. R., El Haddad, I., and Prévôt, A. S. H.: Local incomplete combustion emissions define the PM2.5 oxidative potential in Northern India, Nat. Commun., 15, 3517, https://doi.org/10.1038/s41467-024-47785-5, 2024.

Borlaza, L. J. S., Uzu, G., Ouidir, M., Lyon-Caen, S., Marsal, A., Weber, S., Siroux, V., Lepeule, J., Boudier, A., Jaffrezo, J.-L., Slama, R., Lyon-Caen, S., Siroux, V., Lepeule, J., Philippat, C., Slama, R., Hofmann, P., Hullo, E., Llerena, C., Quentin, J., Pin, I., Eyriey, E., Licinia, A., Vellement, A., Morin, X.,

781   Morlot, A., and the SEPAGES cohort study group: Personal exposure to PM2.5 oxidative potential
782   and its association to birth outcomes, J. Expo. Sci. Environ. Epidemiol.,
783   https://doi.org/10.1038/s41370-022-00487-w, 2022.

784   Calas, A., Uzu, G., Martins, J. M. F., Voisin, D., Spadini, L., Lacroix, T., and Jaffrezo, J.-L.: The
785   importance of simulated lung fluid (SLF) extractions for a more relevant evaluation of the
786   oxidative potential of particulate matter, Sci. Rep., 7, 11617, https://doi.org/10.1038/s41598-
787   017-11979-3, 2017.

788   Calas, A., Uzu, G., Kelly, F. J., Houdier, S., Martins, J. M. F., Thomas, F., Molton, F., Charron, A.,
789   Dunster, C., Oliete, A., Jacob, V., Besombes, J.-L., Chevrier, F., and Jaffrezo, J.-L.: Comparison
790   between five acellular oxidative potential measurement assays performed with detailed
791   chemistry on PM10 samples from the city of Chamonix (France), Atmospheric Chem. Phys., 18,
792   7863–7875, https://doi.org/10.5194/acp-18-7863-2018, 2018.

793   Cassee, F. R., Héroux, M.-E., Gerlofs-Nijland, M. E., and Kelly, F. J.: Particulate matter beyond mass:
794   recent health evidence on the role of fractions, chemical constituents and sources of emission,
795   Inhal. Toxicol., 25, 802–812, https://doi.org/10.3109/08958378.2013.850127, 2013.

796   Charrier, J. G. and Anastasio, C.: On dithiothreitol (DTT) as a measure of oxidative potential for
797   ambient particles: evidence for the importance of soluble transition metals, Atmospheric Chem.
798   Phys., 12, 9321–9333, https://doi.org/10.5194/acp-12-9321-2012, 2012.

799   Charrier, J. G., Richards-Henderson, N. K., Bein, K. J., McFall, A. S., Wexler, A. S., and Anastasio, C.:
800   Oxidant production from source-oriented particulate matter - Part 1: Oxidative potential using
801   the dithiothreitol (DTT) assay, Atmospheric Chem. Phys., 15, 2327–2340,
802   https://doi.org/10.5194/acp-15-2327-2015, 2015.

803   Charrier, J. G., McFall, A. S., Vu, K. K.-T., Baroi, J., Olea, C., Hasson, A., and Anastasio, C.: A bias in the
804   "mass-normalized" DTT response – An effect of non-linear concentration-response curves for
805   copper and manganese, Atmos. Environ., 144, 325–334,
806   https://doi.org/10.1016/j.atmosenv.2016.08.071, 2016.

807   Cho, A. K., Sioutas, C., Miguel, A. H., Kumagai, Y., Schmitz, D. A., Singh, M., Eiguren-Fernandez, A.,
808   and Froines, J. R.: Redox activity of airborne particulate matter at different sites in the Los Angeles
809   Basin, Environ. Res., 99, 40–47, https://doi.org/10.1016/j.envres.2005.01.003, 2005.

810   Council of the European Union: Proposal for a Directive of the European Parliament and of the
811   Council on ambient air quality and cleaner air for Europe, Brussels, 2024.

812   Dabass, A., Talbott, E. O., Rager, J. R., Marsh, G. M., Venkat, A., Holguin, F., and Sharma, R. K.:
813   Systemic inflammatory markers associated with cardiovascular disease and acute and chronic
814   exposure to fine particulate matter air pollution (PM2.5) among US NHANES adults with
815   metabolic syndrome, Environ. Res., 161, 485–491, https://doi.org/10.1016/j.envres.2017.11.042,
816   2018.

817   Daellenbach, K. R., Stefenelli, G., Bozzetti, C., Vlachou, A., Fermo, P., Gonzalez, R., Piazzalunga, A.,
818   Colombi, C., Canonaco, F., Hueglin, C., Kasper-Giebl, A., Jaffrezo, J. L., Bianchi, F., Slowik, J. G.,
819   Baltensperger, U., El-Haddad, I., and Prévôt, A. S. H.: Long-term chemical analysis and organic
820   aerosol source apportionment at nine sites in central Europe: Source identification and
821   uncertainty assessment, Atmospheric Chem. Phys., 17, 13265–13282,
822   https://doi.org/10.5194/acp-17-13265-2017, 2017.

Danehy, J. P., Elia, V. J., and Lavelle, C. J.: Alkaline decomposition of organic disulfides. IV. Limitation on the use of Ellman's reagent. 2,2'-Dinitro-5,5'-dithiodibenzoic acid, J. Org. Chem., 36, 1003–1005, https://doi.org/10.1021/jo00806a036, 1971.

Dominutti, P. A., Borlaza, L. J. S., Sauvain, J.-J., Ngoc Thuy, V. D., Houdier, S., Suarez, G., Jaffrezo, J.-L., Tobin, S., Trébuchon, C., Socquet, S., Moussu, E., Mary, G., and Uzu, G.: Source apportionment of oxidative potential depends on the choice of the assay: insights into 5 protocols comparison and implications for mitigation measures, Environ. Sci. Atmospheres, 10.1039.D3EA00007A, https://doi.org/10.1039/D3EA00007A, 2023.

Donaldson, K., Stone, V., Seaton, A., and MacNee, W.: Ambient particle inhalation and the cardiovascular system: Potential mechanisms, Environ. Health Perspect., 109, 523–527, https://doi.org/10.1289/ehp.01109s4523, 2001.

Frezzini, M. A., De Francesco, N., Massimi, L., and Canepari, S.: Effects of operating conditions on PM oxidative potential assays, Atmos. Environ., 268, 118802, https://doi.org/10.1016/j.atmosenv.2021.118802, 2022.

Gao, D., Mulholland, J. A., Russell, A. G., and Weber, R. J.: Characterization of water-insoluble oxidative potential of PM2.5 using the dithiothreitol assay, Atmos. Environ., 224, 117327, https://doi.org/10.1016/j.atmosenv.2020.117327, 2020.

Gao, Y., Wang, P., Chu, Y., Kang, F., Cheng, Y., Repo, E., Feng, M., Yu, X., and Zeng, H.: Redox property of coordinated iron ion enables activation of O2 via in-situ generated H2O2 and additionally added H2O2 in EDTA-chelated Fenton reaction, Water Res., 248, 120826, https://doi.org/10.1016/j.watres.2023.120826, 2024.

Grandesso, E., Kowalewski, K., and Perez Ballesta, P.: First EC-JRC PAHs inter-laboratory comparison on PM10 quartz filters., European Commission. Joint Research Centre. Institute for Environment and Sustainability., Luxembourg, 2012.

Guascito, M. R., Lionetto, M. G., Mazzotta, F., Conte, M., Giordano, M. E., Caricato, R., De Bartolomeo, A. R., Dinoi, A., Cesari, D., Merico, E., Mazzotta, L., and Contini, D.: Characterisation of the correlations between oxidative potential and in vitro biological effects of PM10 at three sites in the central Mediterranean, J. Hazard. Mater., 448, 130872, https://doi.org/10.1016/j.jhazmat.2023.130872, 2023.

Hart, J. E., Liao, X., Hong, B., Puett, R. C., Yanosky, J. D., Suh, H., Kioumourtzoglou, M.-A., Spiegelman, D., and Laden, F.: The association of long-term exposure to PM2.5 on all-cause mortality in the Nurses' Health Study and the impact of measurement-error correction, Environ. Health, 14, 38, https://doi.org/10.1186/s12940-015-0027-6, 2015.

He, L. and Zhang, J. (Jim): Particulate matter (PM) oxidative potential: Measurement methods and links to PM physicochemical characteristics and health effects, Crit. Rev. Environ. Sci. Technol., 53, 177–197, https://doi.org/10.1080/10643389.2022.2050148, 2022.

Huang, H., Yang, L., Liu, Y., Dong, G.-H., Chen, L., Li, S., Guo, Y., Xie, B., and Chen, G.: Long-term ambient air pollution exposure and DNA methylation of peripheral brain-derived neurotrophic factor promoter, Ecotoxicol. Environ. Saf., 244, 114061, https://doi.org/10.1016/j.ecoenv.2022.114061, 2022.

Kelly, F. J. and Fussell, J. C.: Role of oxidative stress in cardiovascular disease outcomes following exposure to ambient air pollution, Free Radic. Biol. Med., 110, 345–367, https://doi.org/10.1016/j.freeradbiomed.2017.06.019, 2017.

866   Kumagai, Y., Koide, S., Taguchi, K., Endo, A., Nakai, Y., Yoshikawa, T., and Shimojo, N.: Oxidation of
867   proximal protein sulfhydryls by phenanthraquinone, a component of diesel exhaust particles,
868   Chem. Res. Toxicol., 15, 483–489, https://doi.org/10.1021/tx0100993, 2002.

869   Laden, F., Schwartz, J., Speizer, F. E., and Dockery, D. W.: Reduction in Fine Particulate Air
870   Pollution and Mortality, Am. J. Respir. Crit. Care Med., 173, 667–672,
871   https://doi.org/10.1164/rccm.200503-443OC, 2006.

872   Leni, Z., Cassagnes, L. E., Daellenbach, K. R., Haddad, I. E., Vlachou, A., Uzu, G., Prévôt, A. S. H.,
873   Jaffrezo, J. L., Baumlin, N., Salathe, M., Baltensperger, U., Dommen, J., and Geiser, M.: Oxidative
874   stress-induced inflammation in susceptible airways by anthropogenic aerosol, PLoS ONE, 15, 1–
875   17, https://doi.org/10.1371/journal.pone.0233425, 2020.

876   Lepeule, J., Laden, F., Dockery, D., and Schwartz, J.: Chronic Exposure to Fine Particles and
877   Mortality: An Extended Follow-up of the Harvard Six Cities Study from 1974 to 2009, Environ.
878   Health Perspect., 120, 965–970, https://doi.org/10.1289/ehp.1104660, 2012.

879   Li, N., Sioutas, C., Cho, A., Schmitz, D., Misra, C., Sempf, J., Wang, M., Oberley, T., Froines, J., and Nel,
880   A.: Ultrafine particulate pollutants induce oxidative stress and mitochondrial damage., Environ.
881   Health Perspect., 111, 455–460, https://doi.org/10.1289/ehp.6000, 2003.

882   Li, N., Xia, T., and Nel, A. E.: The role of oxidative stress in ambient particulate matter-induced lung
883   diseases and its implications in the toxicity of engineered nanoparticles, Free Radic. Biol. Med., 44,
884   1689–1699, https://doi.org/10.1016/j.freeradbiomed.2008.01.028, 2008.

885   Li, Q., Wyatt, A., and Kamens, R. M.: Oxidant generation and toxicity enhancement of aged-diesel
886   exhaust, Atmos. Environ., 43, 1037–1042, https://doi.org/10.1016/j.atmosenv.2008.11.018,
887   2009.

888   Marsal, A., Slama, R., Lyon-Caen, S., Borlaza, L. J. S., Jaffrezo, J.-L., Boudier, A., Darfeuil, S., Elazzouzi,
889   R., Gioria, Y., Lepeule, J., Chartier, R., Pin, I., Quentin, J., Bayat, S., Uzu, G., Siroux, V., and the
890   SEPAGES cohort study group: Prenatal Exposure to PM2.5 Oxidative Potential and Lung Function
891   in Infants and Preschool- Age Children: A Prospective Study, Environ. Health Perspect., 131,
892   017004, https://doi.org/10.1289/EHP11155, 2023.

893   Miljevic, B., Hedayat, F., Stevanovic, S., Fairfull-Smith, K. E., Bottle, S. E., and Ristovski, Z. D.: To
894   Sonicate or Not to Sonicate PM Filters: Reactive Oxygen Species Generation Upon Ultrasonic
895   Irradiation, Aerosol Sci. Technol., 48, 1276–1284,
896   https://doi.org/10.1080/02786826.2014.981330, 2014.

897   Molina, C., Andrade, C., Manzano, C. A., Richard Toro, A., Verma, V., and Leiva-Guzmán, M. A.:
898   Dithiothreitol-based oxidative potential for airborne particulate matter: an estimation of the
899   associated uncertainty, Environ. Sci. Pollut. Res., 27, 29672–29680,
900   https://doi.org/10.1007/s11356-020-09508-3, 2020.

901   Nicholson, S., Baccarelli, A., and Prada, D.: Role of brain extracellular vesicles in air pollution-
902   related cognitive impairment and neurodegeneration, Environ. Res., 204, 112316,
903   https://doi.org/10.1016/j.envres.2021.112316, 2022.

904   Park, M., Joo, H. S., Lee, K., Jang, M., Kim, S. D., Kim, I., Borlaza, L. J. S., Lim, H., Shin, H., Chung, K. H.,
905   Choi, Y.-H., Park, S. G., Bae, M.-S., Lee, J., Song, H., and Park, K.: Differential toxicities of fine
906   particulate matters from various sources, Sci. Rep., 8, 17007, https://doi.org/10.1038/s41598-
907   018-35398-0, 2018.

908 Sauvain, J. J., Deslarzes, S., and Riediker, M.: Nanoparticle reactivity toward dithiothreitol,
909 Nanotoxicology, 2, 121–129, https://doi.org/10.1080/17435390802245716, 2008.

910 Shahpoury, P., Harner, T., Lammel, G., Lelieveld, S., Tong, H., and Wilson, J.: Development of an
911 antioxidant assay to study oxidative potential of airborne particulate matter, Atmospheric Meas.
912 Tech., 12, 6529–6539, https://doi.org/10.5194/amt-12-6529-2019, 2019.

913 Shahpoury, P., Zhang, Z. W., Filippi, A., Hildmann, S., Lelieveld, S., Mashtakov, B., Patel, B. R., Traub,
914 A., Umbrio, D., Wietzoreck, M., Wilson, J., Berkemeier, T., Celo, V., Dabek-Zlotorzynska, E., Evans,
915 G., Harner, T., Kerman, K., Lammel, G., Noroozifar, M., Pöschl, U., and Tong, H.: Inter-comparison of
916 oxidative potential metrics for airborne particles identifies differences between acellular
917 chemical assays, Atmospheric Pollut. Res., 13, 101596,
918 https://doi.org/10.1016/j.apr.2022.101596, 2022.

919 Shankar, K. and Mehendale, H. M.: Oxidative Stress, Third Edit., Elsevier, 735–737 pp.,
920 https://doi.org/10.1016/B978-0-12-386454-3.00345-6, 2014.

921 Sies, H.: On the history of oxidative stress: Concept and some aspects of current development,
922 Curr. Opin. Toxicol., 7, 122–126, https://doi.org/10.1016/j.cotox.2018.01.002, 2018.

923 Thbayh, D. K., Palusiak, M., Viskolcz, B., and Fiser, B.: Comparative study of the antioxidant
924 capability of EDTA and Irganox, Heliyon, 9, e16064,
925 https://doi.org/10.1016/j.heliyon.2023.e16064, 2023.

926 Uzu, G., Sauvain, J. J., Baeza-Squiban, A., Riediker, M., Hohl, M. S. S., Val, S., Tack, K., Denys, S.,
927 Pradère, P., and Dumat, C.: In vitro assessment of the pulmonary toxicity and gastric availability of
928 lead-rich particles from a lead recycling plant, Environ. Sci. Technol., 45, 7888–7895,
929 https://doi.org/10.1021/es200374c, 2011.

930 Verlhac, S., Leoz, E., Albinet, A., Cabillic, J., Lalere, B., and Fallot, C.: Comparaison interlaboratoires
931 sur l'analyse des HAP dans l'air ambiant, Laboratoire Central de Surveillance de la Qualité de l'Air,
932 2014.

933 Weichenthal, S., Lavigne, E., Evans, G., Pollitt, K., and Burnett, R. T.: Ambient PM2.5 and risk of
934 emergency room visits for myocardial infarction: impact of regional PM2.5 oxidative potential: a
935 case-crossover study, Environ. Health, 15, 46, https://doi.org/10.1186/s12940-016-0129-9,
936 2016a.

937 Weichenthal, S., Crouse, D. L., Pinault, L., Godri-Pollitt, K., Lavigne, E., Evans, G., van Donkelaar, A.,
938 Martin, R. V., and Burnett, R. T.: Oxidative burden of fine particulate air pollution and risk of
939 cause-specific mortality in the Canadian Census Health and Environment Cohort (CanCHEC),
940 Environ. Res., 146, 92–99, https://doi.org/10.1016/j.envres.2015.12.013, 2016b.

941 Weichenthal, S., Shekarrizfard, M., Traub, A., Kulka, R., Al-Rijleh, K., Anowar, S., Evans, G., and
942 Hatzopoulou, M.: Within-City Spatial Variations in Multiple Measures of PM 2.5 Oxidative
943 Potential in Toronto, Canada, Environ. Sci. Technol., 53, 2799–2810,
944 https://doi.org/10.1021/acs.est.8b05543, 2019.

945 Weichenthal, S. A., Lavigne, E., Evans, G. J., Godri Pollitt, K. J., and Burnett, R. T.: Fine particulate
946 matter and emergency room visits for respiratory illness: Effect modification by oxidative
947 potential, Am. J. Respir. Crit. Care Med., 194, 577–586, https://doi.org/10.1164/rccm.201512-
948 2434OC, 2016c.

949 WHO: Review of evidence on health aspects of air pollution REVIHAAP Project- Technical Report,
950 World Health Organization, Regional Office for Europe, 2013.

951 WHO: WHO Global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen
952 dioxide, sulfur dioxide and carbon monoxide, World Health Organization, 2021.

953 WHO: Sustainable Development Goal indicator 3.9.1: mortality attributed to air pollution, World
954 Health Organization, 2024.

955 Wilker, E. H., Osman, M., and Weisskopf, M. G.: Ambient air pollution and clinical dementia:
956 systematic review and meta-analysis, BMJ, e071620, https://doi.org/10.1136/bmj-2022-071620,
957 2023.

958 Zare Sakhvidi, M. J., Yang, J., Lequy, E., Chen, J., De Hoogh, K., Letellier, N., Mortamais, M., Ozguler,
959 A., Vienneau, D., Zins, M., Goldberg, M., Berr, C., and Jacquemin, B.: Outdoor air pollution exposure
960 and cognitive performance: findings from the enrolment phase of the CONSTANCES cohort,
961 Lancet Planet. Health, 6, e219–e229, https://doi.org/10.1016/S2542-5196(22)00001-8, 2022.

962
963
964