Deliverable D31 (D4.10)

Summary: novel health effect indicator pilots, sustainability, associated benefits

RI-URBANS

Research Infrastructures Services Reinforcing Air Quality Monitoring Capacities in European Urban & Industrial AreaS (GA n. 101036245)

By

ISGlobal, CSIC, PSI, CNRS & UHEL

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Deliverable D31 (D4.10): Summary: novel health effect indicator pilots, sustainability, associated benefits

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1. About this document

RI-URBAN's WP4 focuses on implementing 5 pilots in different European cities. Pilot 4 corresponds to Novel health indicators, aiming at validating measurement techniques and approaches to assess health effects by complementing existing air quality policies with measures directly targeting novel air quality metrics and health-relevant emission sources.

This deliverable addresses T4.4 on novel health indicators of nanoparticles and PM components and source contributions. The focus of this deliverable is to provide a summary of novel health indicators, their sustainability, and benefits for the Air Quality Monitoring Networks (AQMNs) and air quality policies.

This document contains a summary of the implementation, findings, sustainability, and associated benefits of pilot studies evaluating novel health-relevant air pollution indicators across four European cities.

This is a public document that will be distributed to all RI-URBANS partners for their use and submitted to the European Commission as a RI-URBANS deliverable D31 (D4.10). This document can be downloaded at https://riurbans.eu/work-package-4/#deliverables-wp4.

2. Introduction

Air pollution is detrimental to health; however, the specific mechanisms and components or features that have the greatest impact remain poorly understood. The most recent European Ambient Air Quality Directive 2024/2881 (EC, 2024), and the 2021 World Health Organization (WHO), now recommend or force the regular monitoring of "novel" pollutants like ultrafine particles (UFP) and black carbon (BC), recognising them as pollutants of concern due to their potential to impact health (EC, 2024; WHO, 2021). The harmonised and regular monitoring of these pollutants are important to create long-term time-series that can be used in health studies to elucidate their role and quantify their impacts. However, because the latest new EU Air Quality Directive is still to be implemented, a long time-series of these novel pollutants will be available in a few years. Additionally, even when the data is available currently from a number of research supersites, measurement protocols are not harmonised and this makes comparison of the data. The measurement of different particle size ranges might complicate comparison in epidemiological studies.

While harmonised measurements of novel pollutants and other metrics are desirable to improve comparability, the creation of long-term databases for off-line metrics like oxidative potential (OP) may be challenging, for example due to the elevated cost of laboratory analysis. Moreover, because epidemiological studies often require daily data, analyzing associations based on non-daily measurements of offline pollutants is statistically more complex.

The RI-URBANS pilot (T4.4) epidemiological studies had the opportunity to collect 2021-2023 data and generate datasets for recently established pollutants and metrics of concern using harmonised analytical methodologies or instrumental configurations. The data originating from the pilots were also analysed by the same research teams to ensure similar sample/data treatment across sites, which enables direct comparison of the epidemiological results. In these pilot cities, we collected data, on a daily basis for more than a year, for a number of novel and/or unregulated pollutants and other metrics that have been highlighted in the literature as potential health hazards, such as UFP, ultrafine particle number size distribution (PNSD) sources, BC sources, PM sources, particulate matter (PM) chemistry and its OP.

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The RI-URBANS pilot studies (WP4, T4.4) aimed to associate short-term changes in novel unregulated pollutant concentrations and other metrics, such as OP of PM, with daily changes in all-cause mortality from four European cities (Athens, Barcelona, Paris and Zurich). Because the data was measured, processed and analysed in a similar manner, the results are expected to be comparable. However, an important limitation is the relatively short datasets, which reduces the statistical power of the results, but this is conditioned by the duration of the project. Quasi-Poisson regression models were used to quantify the associations in each city, and the results were averaged using a random effect meta-analysis model.

The pilot study is important for policy making as it provided insights on the effects of novel unregulated air pollutants and other metrics on health. This deliverable summarizes the main results of the work on the novel health indicators in RI-URBANS and discusses the sustainability and added value of these novel indicators.

3. Novel health indicators in pilots: summary of the findings within the RI-URBANS project

In RI-URBANS WP4, we assessed the **short-term associations between a large number of (novel) air pollutants** (97 PM-related pollutants) **and mortality in four pilot cities: Athens, Barcelona, Paris, and Zurich**. The pilots managed to obtain daily data on most pollutants for a period of three years.

Table 1. Periods of data availability for each of the cities studied in the pilot study.

Group of pollutants	**Athens (Thissio)**	**Barcelona (Palau Reial)**	**Paris (Les Halles)**	**Zurich (Kaserne)**
PNSD	01-2021 to 12-2023	01-2021 to 12-2023	01-2021 to 12-2023	01-2018 to 07-2018
$PM_{2.5}$ and PM_{10}	01-2021 to 12-2023	01-2021 to 12-2023	01-2021 to 12-2023	01-2018 to 12-2019, 01-2021 to 12-2022
PM chemistry	06-2022 to 06-2023	03-2022 to 02-2023	04-2022 to 03-2023	06-2018 to 05-2019
BC	01-2021 to 12-2023	01-2021 to 12-2023	01-2021 to 12-2023	01-2018 to 12-2019, 01-2021 to 12-2022
OP	06-2022 to 06-2023	03-2022 to 02-2023	04-2022 to 09-2023	06-2018 to 05-2019

In these pilot cities, as part of RI-URBANS, a **harmonised air pollution data collection protocol** was established, providing a rich air quality dataset in which all the samples from all the cities were measured in the same laboratory. The OP variables were measured from PM filter-based samples at the Institut des Géosciences de l'environnement from the University of Grenoble (France), and the inorganic chemical composition was performed at the Institute of Environmental Assessment and Water Research at the Spanish National Research Council (Spain). Additionally, the protocols for the measurement of online air pollutants were also homogeneous within each institutional capacity. PNSD data could not be fully harmonized in terms of the size range covered given the differences in the instrumentation used, but all the sites followed the ACTRIS standards. Further details on the air pollution data collection can be found in Deliverables D1 (D1.1) and D30 (D4.9). These harmonization efforts greatly improved

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the comparability among the different cities, providing much robust results in the meta-analysis due to the harmonisation.

On the other hand, the largest limitation of the work performed within the pilot cities WP4 was the relatively short time series. **Three years of data could be considered a too short period for a time series analysis**, depending on the size of the cities (and thus, the total number of deaths in the period, which is a determinant parameter of the statistical power; see D9 (D2.1) for further information. Moreover, the use of mortality data from burials, which includes accidental deaths, is an additional limitation in this study.

In this section, we provide a short summary of the short-term associations of several novel and regulated air pollution metrics and natural and/or all cause mortality in four European cities (Athens, Barcelona, Paris and Zurich). The different analyses were performed within the Pilot 4 (Task 4.4) from WP4 of the RI-URBANS project. Because the data was measured, processed and analyzed in a similar manner, the results are expected to be comparable across cities. However, it is worth noting that due to the short period of the time-series from pilots, the city-specific epidemiological models may have lacked statistical power to detect small associations between air pollutant metrics and mortality. The associations between air pollutant metrics and mortality were evaluated using Quasi-Poisson regression models in each city independently, and the results were combined using a random-effect meta-analysis model.

The results are only very briefly summarized in this deliverable as the details can be found in RI-URBANS D29 (D4.8) on best practices for evaluation of nanoparticles and health for application in pilots (link available soon).

3.1 PNSD and its sources

A significant increase in mortality risk per IQR increase was observed for Aitken, Accumulation, and particle number concentrations in size 25-800 nm, especially at lags 4–7. Although the associations were maintained after adjusting for $PM_{2.5}$ concentrations (except for the Aitken mode), they weakened after adjusting for NO_2 (and lost significance).

Regarding sources, Regional_2 (regional PM dominated by secondary aerosols) showed consistent positive associations with mortality (maintained after adjusting for $PM_{2.5}$ and NO_2 individually), and mixed traffic also showed positive associations with mortality at specific lags (but association was lost after adjusting for $PM_{2.5}$ and went into the opposite direction - protective effect- for NO_2).

3.2 eBC and its sources

Total eBC and the fraction of eBC from residential combustion sources (solid fuels such as wood burning, from residential and commercial activities) were significantly associated with increased risk of mortality. These associations remained after adjusting for $PM_{2.5}$ and NO_2, mostly for eBC from residential combustion.

3.3 PM and its sources

$PM_{2.5}$ was associated with increased risk of mortality at later lags (5–7) but these were not observed for the coarse fraction ($PM_{2.5\text{-}10}$) or PM_{10} nor in the two-pollutant models adjusted for NO_2.

The primary biogenic PM_{10} source was associated with a **decreased risk** of mortality at lag 4 and this association was maintained after adjusting for NO_2 but not after adjusting for PM_{10}. The PM_{10} secondary organic aerosol (SOA 1) was positively associated with increased mortality at lag 6, and the association was maintained after the inclusion of PM_{10} in the two-pollutant model.

3.4 PM chemical composition

We found positive associations between mortality and NH_4^+, Ca^{2+}, Ca, Fe, Mg, Mn (only $PM_{2.5}$), and Ti (only $PM_{2.5}$), especially in $PM_{2.5}$. These associations were consistent in the two-pollutant models after adding the corresponding fraction ($PM_{2.5}$ or PM_{10}) and NO_2. Mn and Fe were particularly relevant. These two PM components arise in urban areas mainly from vehicular brake discs and pads.

3.5 PM oxidative potential

No consistent associations were found between OP of PM and mortality in the meta-analysis. Some OP metrics (e.g. DTT normalised by mass in PM10) showed protective effects (decreased risk), but results should be interpreted cautiously due to potential collinearity.

4. Sustainability

The sustainability of the analysis of the impact of novel air pollutants and other metrics on mortality by using an epidemiological time series approach refers to the ability to continuously collect and analyse air pollutants over the long term without depleting financial resources, overburdening personnel, and/or harming the environment. This type of analysis requires data to be collected on a daily basis, which is feasible through online monitoring systems but can be significantly more challenging when relying on offline sampling and laboratory analysis. Specifically, it involves:

Economic sustainability: Air pollution data collection is expensive, both regarding the acquisition of instrumentation (and its maintenance and need of frequent calibrations), as well as the laboratory consumables and material in case of the analyses of filter-based samples. For long-term sustainable data collection, it has to be cost-effective, with funding models that support long-term operations, equipment maintenance, and data management.

Human resource sustainability: Maintaining a skilled and adequately staffed workforce without causing burnout or excessive turnover, and investing in training and safety. Processing a large amount of off-line daily samples (e.g daily filter samples for different PM fractions) may be a too high burden to be maintained over prolonged periods, both at the laboratory and field levels.

Environmental sustainability: One should also ensure the minimisation of the ecological footprint of sampling activities (e.g., reducing waste, consumables, using low-impact technologies).

Operational sustainability: Designing workflows and logistics that are efficient, scalable, and adaptable to changing conditions or technologies.

Further detail is provided in the following subsections about the long-term sustainability for the collection of the air pollution data and mortality/morbidity datasets following the above-mentioned categorization of sustainability challenges.

4.1 Air pollutant measurements

4.1.1 Feasibility of air pollution data collection for novel metrics

Article 10 of the European Ambient Air Quality Directive 2024/2883/CE (EC, 2024) requires that Member States shall establish at least one urban background monitoring supersite per 10 million inhabitants. These supersites must be capable of measuring UFP, PNSD, and BC. Moreover, the content of a few components in $PM_{2.5}$ must be determined in order to identify possible origins of PM. Additionally, the monitoring of OP of PM is recommended at these sites, among other measurements.

According to the same Article, measurements at supersites can be either fixed or indicative. Fixed measurements must be continuous throughout the year, with a minimum annual data coverage of 80% for UFP and BC, and 45% for OP and the PM chemical composition. Indicative measurements, on the other hand, may be performed at regular intervals or randomly, but must achieve at least 13% annual data coverage for all metrics.

For epidemiological time-series analyses, fixed measurements are particularly valuable due to their higher temporal resolution and broader data coverage, which enhance the reliability of health impact assessments. The new directive requirements and recommendations should enhance the ability to perform epidemiological analyses on UFP and BC, as well as OP and chemical composition of PM, and their sources.

Additionally, there is the need to **measure novel pollutants/metrics alongside regulated pollutants** in order to adjust epidemiological models for the confounding effects of these emerging pollutants/metrics. That is, both emerging and regulated pollutants should be measured at the same station.

Challenges with the measurements of new air quality metrics: the lack of standardized measurement protocols limits comparability across studies

Novel air pollution metrics often lack harmonized measurement protocols, which hinders the comparability of epidemiological findings across different locations. For instance, in WP4-T4.4, most of the cities measured PNSD with a lower cut-off diameter of 8–10 nm, with the exception of Zurich where the cut-off was at 17 nm because we had to use previously collected datasets due to issues encountered during the PNSD data collection of the pilot period. Since smaller particles typically show larger number concentrations, these differences in instrumentation can lead to significant discrepancies in UFP concentrations, with lower cut-off diameters likely reporting higher concentrations. Harmonising these measurements to include the smaller particles would improve comparability but may require costly equipment upgrades and technical support. A similar issue arose in WP2 regarding OP of PM. Although OP data was available for the city of Athens, this city was excluded from the meta-analysis for using an analytical protocol that differed from the other cities, which made the data incompatible (this is not the case for WP4 - the results of which are presented here - where OP was measured for all the cities in the same laboratory). A laboratory intercomparison exercise (RI-URBANS Service Tool 4) confirmed that different OP measurement techniques can yield inconsistent results. Ideally, all air pollutants should be measured using standardized protocols to ensure data comparability. With the exception of the PNSD size range, WP4 successfully harmonized measurements across pilot cities, enabling their inclusion in the epidemiological random-effects meta-analysis. PNSD data were also included but with the limitation exposed above.

It is important to note that even if PM speciation analyses are harmonised, the application of different receptor modelling tools or the same tools by different experts may yield to different PM source apportionment results. In this case, not only the PM speciation was harmonised but a single group applied the US-EPA Positive Matrix Factorization (PMF) to all datasets to be sure that the source contributions were calculated also in a harmonised way.

4.1.2 Economical sustainability of long-term measurements

Long-term air quality monitoring is essential for understanding population exposure and supporting epidemiological research. However, the economic sustainability of such efforts - particularly when relying on offline measurement techniques - presents significant challenges:

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High operational costs of offline methods

Offline sampling methods, such as filter-based collection followed by laboratory analysis, **are resource-intensive.** They require:

- Skilled laboratory personnel for sample preparation, handling, and analysis.
- Expensive consumables (e.g., filters, solvents, reagents).
- Specialized instrumentation (e.g., for chemical speciation, oxidative potential, or gravimetric analysis).
- These costs scale rapidly with increased sampling frequency and the number of pollutants or PM fractions analyzed (e.g., $PM_{2.5}$, PM_{10}).

Unsustainability of daily sampling

Daily offline sampling across multiple PM fractions generates a **large number of samples**, which may **overwhelm laboratory capacity**. Additionally, it increases storage and logistics costs. Year-round monitoring using daily filter-based sampling and detailed chemical speciation and OP analysis **is potentially economically unfeasible** given the large costs, lack of space, and current availability of resources in most laboratories.

Centralized analysis bottlenecks

As evidenced by the lab intercomparison exercise for OP of PM, relying on a single laboratory to process samples from multiple cities or countries would be ideal. However it may end up in:

- Delays in data processing and reporting.
- Logistical complexity in sample transport and quality assurance.
- Risk of analytical inconsistencies, especially if protocols are not fully harmonized.
- This **centralized model is not scalable or resilient** for long-term, multi-site monitoring, urging the need for harmonized protocols and training of other laboratories.

If a centralised laboratory is not available for OP of PM a periodical intercomparison of results using the same harmonised protocol is required.

Need for cost-effective alternatives

To ensure economic sustainability, there is a growing need to:

- Develop and expand the use of cost-effective online, automated instruments for continuous monitoring.
- Promote decentralized analysis capacity, supported by inter-laboratory calibration and quality control frameworks.

4.2 Mortality or morbidity datasets in the context of long-term evaluation of novel air pollutant metrics

The **sustainability of collecting daily mortality data**—and, where available, other daily morbidity indicators—**is well supported** in Europe, as these datasets are routinely compiled by official health authorities or national administrative bodies. This institutionalized data flow ensures long-term continuity and reliability, which are key pillars of sustainable surveillance systems. However, a significant challenge arises when attempting to align these health datasets with emerging novel air pollutant metrics. While mortality data are systematically collected, **access to the most recent records** (e.g., daily death counts or hospital admissions) **is often delayed**, with official releases typically **lagging by one to two years**. This time gap can hinder timely analyses and limit the responsiveness of public health interventions. Even when mortality data is made available (i.e. after being processed), additional challenges may be encountered. For example, the payment of fees may be needed to access the data; data can be censored or aggregated to preserve privacy; or data may not be extracted from official facilities, requiring researchers to conduct their statistical analyses in the official premises under strict security measures.

In the absence of timely official records on daily mortality or other health indicators, **alternative data sources** - such as provisional (non-final) mortality data or daily burial counts - can be considered. These alternatives may offer more immediate insights, especially in contexts where rapid assessments are needed. However, their use comes with important **limitations** that can affect the robustness and interpretability of the results. For instance, burial data, while available in near real-time in some settings, include deaths from accidental causes. These causes are typically excluded from time series analyses focused on environmental exposures, as they are not plausibly linked to air pollution or similar risk factors. Including such deaths may introduce noise and bias into the analysis, potentially weakening the observed associations. In addition, it is unfeasible to investigate cause-specific associations when using burial data.

Therefore, while alternative datasets can serve as useful proxies in the short term, they should be interpreted with caution and their limitations should be acknowledged.

5. Associated benefits of the health evaluation of novel air pollutant metrics in pilot cities

This study demonstrates the feasibility of using novel air quality metrics in a multi-city time-series epidemiological analysis. The **harmonized protocol was key in ensuring comparability across cities**. However, one must acknowledge the limitations, which mainly are: (i) the **relatively short duration of the air quality time series** of the pilot cities (with a maximum of three years of harmonised daily data for PNSD, eBC, and PM, and less than two years for OP), (ii) the **heterogeneous mortality data**, since these data needed to be collected for very recent periods they were obtained from different sources (burial registries, provisional official records) which may introduce potential inconsistencies.

There are clear associated benefits of evaluating the short-term impacts on health of novel air pollutants in pilot cities, particularly if this is done combining data from multiple locations using a standardised protocol, as it was the case in the RI-URBANS pilot cities. These benefits include:

- Exploration of effects of novel or non-commonly studied air pollutant metrics on death counts. This information is crucial for future WHO air quality guidelines and future legislation on air quality.
- Identifying which pollutants are most harmful to health enables more effective and targeted regulatory strategies.
- Ultimate reduction in disease and mortality burden which not only saves lives but also decreases hospitalization costs, sick leaves, etc, yielding economic and public health benefits.

The difficulties in maintaining the air quality metric measurements over longer periods of time for some metrics (e.g. daily off-line measurements with laboratory analysis) hinders the applicability of the epidemiological analyses in the long run, which would provide much more robust results as the statistical power increases with additional years of data. The lack of long-term measurements prevent epidemiological models from finding small associations between novel air pollution metrics and health outcomes due to lack of statistical power. The fact that some of the pollutants are still unregulated means that cities are not legally obliged to measure these pollutants, and for this reason, long-term time-series that could be used in epidemiological studies to uncover health effects may be scarce in some areas. While the new EU Directive 2024/2881 (EC, 2024) provides a framework for systematic data collection on UFP, PNSD and BC, the inclusion of OP of PM remains optional, with lower data coverage requirements. Finally, the lack of daily data for offline-measured pollutants poses a significant challenge for time-series epidemiological models. Non-daily data introduce gaps that reduce model accuracy and limit the ability to detect health effects. In the future, online OP measurements may serve as an alternative to offline measurements for producing daily OP data. However, this alternative is likely to come at a higher cost.

Although the results from WP4 were unclear for certain novel metrics (e.g., OP), due to the limitations of this study, the adverse effects of these novel metrics on health cannot be ruled out. We highlight the need for long-term daily monitoring of “novel” air pollutant metrics on multiple sites across the EU, whenever possible, as long-term data is crucial for the development of robust epidemiological models that can detect even small effects on health.

6. Concluding remarks and future considerations

This study highlights the feasibility and value of incorporating novel air pollution metrics—such as ultrafine particles (UFP), black carbon (BC), particle number size distribution (PNSD), and oxidative potential (OP)—into multi-city time-series epidemiological analyses. The harmonized data collection protocols implemented across the RI-URBANS pilot cities were instrumental in ensuring comparability and strengthening the reliability of the results.

Despite the promising findings, several limitations must be acknowledged. The relatively short duration of the time series, the heterogeneity in mortality data sources, and the challenges associated with offline pollutant measurements constrain the statistical power and generalizability of the results. These limitations underscore the need for sustained, long-term monitoring efforts.

Based on the pilot experience we would recommend to: (1) **expand the long-term monitoring** by establishing and maintaining harmonized, high-resolution air quality monitoring networks across Europe, with a particular focus on novel pollutants - ideally, all metrics should be measured at the same sites to support robust epidemiological studies; (2) **use standardized measurement protocols** to be applied in all monitoring stations to ensure data comparability; (3) facilitate **open access to air quality data** through public platforms, and **streamline access to disaggregated health data** (e.g., daily mortality) by reducing administrative barriers while maintaining appropriate data protection standards.

A future in which harmonized, open-access, and long-term air quality datasets—including novel metrics—are routinely collected and integrated with health data across Europe. This would enable the development of robust epidemiological models capable of detecting even subtle health effects, ultimately guiding evidence-based policies that protect public health and reduce the burden of disease.

References

EC, 2024. Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe (recast) [WWW Document]. Off. J. Eur. Union. URL https://eur-lex.europa.eu/eli/dir/2024/2881/oj/eng (accessed 1.31.25).

WHO, 2021. WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide.

Zhu, Y., Hinds, W.C., Kim, S., Shen, S., Sioutas, C., 2002. Study of ultrafine particles near a major highway with heavy-duty diesel traffic. Atmos. Environ. 36, 4323–4335. https://doi.org/10.1016/S1352-2310(02)00354-0